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Metals and Alloys

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COR-TEN CAR CARRIES 4866 LBS. MORE *costs only $42.33 more*

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"We are now building 200 of these box cars . . . each

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The use of COR-TEN in these revenue-increasing cars—built on a production line basis, by the most modern automatic arc-welding and spot-welding equipment—is convincing proof that even in high-speed fabrication COR-TEN can be handled as successfully as ordinary steel.

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U·S·S HIGH TENSILE STEELS

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Radiographic Development in the Casting Industries

BY CHARLES W. BRIGGS

Technical Adviser,
Steel Founders' Society of America,
Cleveland.

This article was read by a man outside of the foundry industry and of high standing in the field of radiography. His comment is worth quotation in part: "This is an exceedingly worthwhile, timely and sane presentation of the radiographic picture as it affects the foundry industry. I do not remember having seen a better one. It has additional interest in that it comes from the foundry industry and reflects the modern trend of thought of the more progressive elements of that industry."

The foundry industry, says the author, is not opposed to the establishment of radiographic standards that are fair. Proper radiographic interpretation is discussed. Poor design is responsible for a large percentage of defective castings, says Mr. Briggs, who advocates that poor design features of castings be discussed with the purchaser. Radiography is of value to many foundrymen as an aid in establishing the manufacturing procedure of a casting.—The Editors.

IN 1895, ROENTGEN, in an experiment involving the emission of ultra-violet light from high vacuum discharges, discovered the X-ray. However, it was not until 1912 that much industrial significance was attached to the idea of non-destructive testing of materials by X-rays. It was during that year that Coolidge introduced a new type of tube which could be operated continuously at higher voltages, used greater currents, and thus increased both the penetrative power and the intensity of the rays. The advent of the Coolidge tube marked the beginning of the effective use of radiography in industry. However, records of the use of X-rays in the casting industries are not as early as this. Some little experimental work was carried on in connection with the non-destructive testing of aluminum castings during the World War, but nothing in the way of routine testing.

Early History

From 1915 to 1920, radiographic facilities and technique improved greatly with the introduction of better power plants, tubes of longer life, and more sensitive film.

It has been only since 1922 that radiography has had serious use in the metal industries. It was during that year that the U. S. Army Arsenal at Watertown, Mass., installed a 200,000 volt 5 milliamp X-ray equipment. This installation raised the thickness limit of steel which could be radiographed commercially from 1½ to 3 in. The arsenal staff, under the direction of Dr. H. H. Lester immediately undertook to inspect all types of castings that were being made for the U. S. Army.

In 1923, Dr. Lester published an account of an examination of steel castings by radiography. His investigations allowed him to make statements concerning the application of the X-ray method. He found that, for practical working conditions, detectability may be placed at 2 per cent, which means that a discontinuity of 0.05 in. in diameter can be detected in steel 2.5 in. thick.

The results that were being obtained at Watertown created considerable interest among engineers generally. Mechanical engineers were much interested in the commercial application of non-destructive testing to pressure equipment castings, and during 1925 Moultrop and Norris published an article on the X-ray examination of steel castings in *Mechanical Engineering*. The work described in the paper was carried out in testing steel castings that were subject to a steam pressure of 1200 lbs. They pointed out that radiography was sufficiently sen-

sitive to show in a steel section a discontinuity of 2 per cent, and that flaws equivalent to 10 or 20 per cent or more of the section were only of importance if their detection and estimation were possible with a satisfactory degree of accuracy.

Shortly after this date, engineers began to demand an X-ray inspection of important castings for high-pressure steam plants. Light aluminum alloy castings began to be prominently used in all types of structural application which required radiography.

The non-destructive testing of metals took another step forward when, in 1929, Dr. R. F. Mehl, with the aid of Drs. Barrett and Doan, completed a systematic research which established the use of gamma rays from radium for the inspection of metal. The gamma-ray method of radiography was immediately applied to steel casting inspection by the U. S. Navy. Important hull and propulsion castings were studied, which resulted in a wide-spread use of gamma-ray radiography during the next eight years throughout all the Navy Yards and naval inspection centers.

First Portable X-Ray Sets

The first portable X-ray sets were introduced in 1930, and in 1932 a 300,000-volt Coolidge tube became available, increasing the thickness of steel that can be commercially X-rayed from 3 to 4½ in. Since then higher voltage tubes have been built, until now one foundry organization is equipped with a 400,000 volt X-ray unit capable of making diagnostic radiographs through 5 in. of steel.

Today, the non-destructive testing of castings, while still considered a special test, is not looked upon by the foundryman with awe and uncertainty. The foundryman has found it to his advantage to keep up with the developments being made in radiography. To help him keep abreast of radiographic activities, a committee on the radiography of castings was organized by the American Foundrymen's Association in 1935. It was their duty to act as a fact-finding committee and to submit a yearly report concerning the progress being made in radiography as applied to the manufacturing, control and inspection of castings. This the committee has done.

The radiographic committee of the A. F. A. held an informative session in 1936 for the purpose of discussing the appearance of radiographs and the interpretation of the shadow markings. The manner in which radiography may be used in the foundry as an aid in solving production problems was also studied. The cost of radiographic equipment was reviewed, as well as presentation of the tabulated results of a questionnaire on the subject of radiography in the steel foundry, which received industry-wide distribution.

Symposium on Radiography

In 1936, another important radiographic event took place which caused considerable interest throughout the metal industries. The American Society for Testing Materials held a Symposium on Radiography and X-Ray Diffraction. From the excellent information presented at this symposium the foundry industry learned that the X-ray method and the gamma-ray method were not competitive methods of non-destructive testing, but instead, were complementary in scope. Foundrymen learned that the advantages of X-ray radiography were those of short exposure times and pronounced contrast of image, while the advantages of gamma-ray radiography were portability and the degree of latitude (the extent of variation in metal section that may be satisfactorily radiographed at one time).

Furthermore, foundrymen learned that if they were required to radiograph light castings on a production basis, they should resort to the use of X-ray equipment, while if they were interested in the non-destructive testing of castings from 4 to 10 in. thick, they may consider using gamma rays.

To carry on the good work that had been started so well by the symposium, the A. S. T. M. organized, in 1937, Committee E-7 on Radiographic Testing, with the hope that all advancements in this country in the technique of radiographic testing and the formation and adoption of radiographic standards would come to the attention of the Committee.

The foundry industry is represented on Committee E-7 and particularly on Sub-Committee I, which concerns itself with the Radiography of Cast Metals. The work of the Sub-Committee is in the formative stage, yet it has prepared a revision of the Recommended Practice for Radiographic Testing of Metal Castings (E 15-29), and has proposed for adoption as a tentative standard, the Gamma-Ray Radiographic Standards for steel castings for steam pressure service, as prepared by the Bureau of Engineering, Navy Department.

The foundry industry is not opposed to the establishment of sets of radiographic standards that are fair in their treatment of the subject. In fact, they welcome them, providing the standards are prepared for castings of a specific application, such as the above Navy standards which are limited to steel castings intended for steam pressure service. The reason that standards of this type are willingly accepted by foundrymen is that they set up standards which may be observed and used as guides. This is quite different from some vague ideas on rejection limits that repose in the minds of the purchasers of castings or their authorized inspectors. The presence of standards sharply defines the situation.

Fig. 1.—Setting up an aluminum casting for radiography by X-rays.
(Courtesy of Aluminum Company of America)

Radiographic Interpretation

One of the most serious drawbacks in the adoption of radiographic methods by casting producers has been the fear of radiographic interpretation. It was felt that minor discontinuities in unimportant sections were given as much consideration as the more important disclosures in critically stressed sections. The situation involves more than fear of the possibility of having this come true, for in some cases it actually happened. These situations resulted largely from the fact that the operating conditions and requirements applicable to the various casting members were not known to the inspectors or to the purchasers.

Such conditions have led casting producers to use caution in accepting unqualified orders calling for castings subject to radiographic examination. Orders of this type mean that the purchaser may radiograph any and all parts of the casting and perhaps reject the casting for some minor defect present in an unimportant section, such as the tie-in sections which carry no important stresses and which may be so designed that their factor of safety is extremely high.

To prevent occurrences of this type, the foundry management should request that the consumer submit marked drawings which designate the places that will be subject to radiographic examination. The thought underlying such a request is that marked drawings

Fig. 2.—Steel castings being radiographed by gamma rays from radium. (Courtesy Lebanon Steel Foundry)

will help the foundryman materially in planning the production of the job. It will enable the operating department to provide for desirable metal feeding and in many cases reduce the use of inserts; in fact, the mold may be produced in a manner differing entirely from production procedures wherein no information as to casting requirements of important or highly stressed areas is given.

The foundry management likewise desires to discuss with the purchaser at the time the order is received the subject of interpretation of the radiographic results, since he desires to know if the purchaser has a set of standards that are reasonable and mutually satisfactory. If the purchaser has no standards, the casting producer will probably suggest that rejection be determined by a joint council of purchaser and foundryman.

There are some who believe that the product of the foundry industry is seldom, if ever, free from defects. In many cases, they have based this opinion on the continued appearance in the technical press of radiographs of defective castings. The fact that the authors usually state that the illustrations presented should not be used as an indication of the quality of castings in general apparently makes no impression.

It so happens that the radiographic methods are well adapted to the non-destructive examination of castings. Welded construction is likewise adaptable to this type of investigation, and it is believed that the technical literature contains as many reproductions of radiographs of defective welds as it does of castings.

Other metal forms have their share of defects also. It so happens that other methods of non-destructive testing are more adaptable, such as in the location of laminations and seams in plate and fabricated shapes.

Radiography An Aid to Designers

Foundrymen have great hopes that radiography will be of material aid in pointing out to designing engineers and purchasers in general that poor design is responsible for a large percentage of the castings that prove defective. For many years foundry engineers have requested that designers make their proposed designs more castable. They have continually suggested that the design engineer consult with them while the design is in the formative stage. If cooperation between designer, purchaser and foundryman existed at that time, many difficulties and much dissatisfaction could be avoided. It is believed that radiography will tend to bring about such cooperation because producers are being confronted with radiographs of castings which are not so designed that it is possible for the foundry to secure the quality of castings that the designer intends to have.

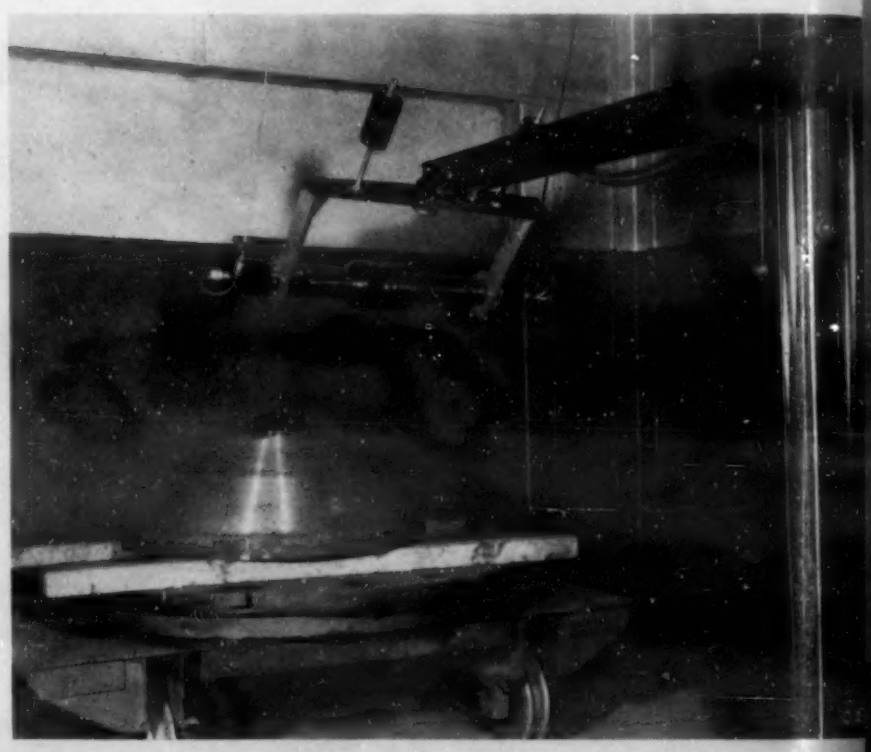


Fig. 3.—Radiographing a steel casting by means of X-rays. (Courtesy American Manganese Steel Division of American Brake Shoe and Foundry Company)

The foundryman today is also insisting to a greater extent that poor design features of castings be discussed with the purchaser. He realizes that the pur-

chaser will reject a defective casting as shown by radiography, even if the designer has designed it so that it could be nothing else but defective. And even though the foundryman can convince the purchaser that poor design is responsible for the defect, the foundryman nevertheless has a defective casting on his hands.

Thus, there is a strong expectation that with the progress of radiography in the casting industry, will come the appreciation by designers of more tolerant designing, since radiography makes it so easy for them to see the results of their handiwork.

If a casting is designed properly, the percentage of defects to be found resulting from manufacturing operations is low. Proof of this statement may be obtained at any foundry where a casting which has been standardized as to design and production details is being made regularly. Radiograph after radiograph will be found to be flawless.

Radiography An Aid in Manufacturing

Radiography is of value to many foundrymen as an aid in establishing the manufacturing procedure of a casting. A pilot casting may be completely radiographed in order to check on casting design and production methods. In this manner, changes can be made to the pattern or mold construction so that the next casting will be a perfect job. This prevents the repetition of a defect in a number of castings, all of which may be rejected.

It is believed that radiography is bringing about greater understanding of the service requirements of a casting. More attention is being given to the highly stressed areas of castings. The result of this has been that defects which previously may have caused rejection are now being repaired and accepted, since the sections in which they occur are not vital ones.

Also, purchasers are more willing to repair castings when they can re-radiograph the casting and observe the condition of the repair. The Bureau of Engineering of the U. S. Navy has found that, because of radiography, it could authorize the repair of certain castings which would have been rejected before the advent of radiography.

Radiography in Aluminum and Steel Castings

In the casting industry radiography has received more attention in the aluminum and steel casting branches.

Aluminum alloy castings such as those being used in the aircraft industry are being inspected by radiography in large numbers. One inspection service reports several thousand castings being inspected weekly by X-rays.

In the steel casting industry high-pressure high-temperature equipment is receiving the bulk of radiographic inspection, though considerable radiographic inspection is being given to structural castings which must operate in very exacting services. Gamma-ray radiography is being favored for the above types of inspection. The U. S. Navy has approximately 4800 milligrams of radium, split up into 19 capsules, for the inspection of castings of the above types purchased by the Navy. The Radium Chemical Co. of New York City has 34 capsules totaling 3800 milligrams of radium available for commercial radiography. Several of the more progressive foundries and users of castings have purchased radium and X-ray equipment for non-destructive testing.

High alloy content steel castings, such as the heat and corrosion resistant cast steels, are frequently inspected by radiography, the X-ray method being favored due to the relatively light sections.

It is believed that in view of the points disclosed above, the radiographic development in the casting industries is equivalent to that found in other industries. It may also be considered a factor in the technical development of the casting industries.

Fig. 4.—Gamma ray set-up on steel castings. (Courtesy of Bonney-Floyd Company)

Hardenability of Molybdenum S. A. E. Steels

This article, characterized by one of our editorial advisory board as "coming up to all my expectations as to quality and importance," contains not only further information on austempering, but describes an improved dilatometer for studying the rate of transformation. It deals with some of the S. A. E. steels, particularly those containing molybdenum. The article may be regarded as supplementing discussions in the Campbell Memorial Lecture by E. S. Davenport last October.—The Editors.

BY ROBERT M. PARKE AND ALVIN J. HERZIG

Climax Molybdenum Co., Detroit, Mich.

THE MEASUREMENT OF THE HARDENABILITY of steel has properly received considerable attention because of the relationship of hardenability to the other important properties of steel. Rapid tests have been devised which adequately determine hardenability of steel for purposes of comparison. If, however, the interest lies not so much in the depth hardness of steel after some defined hardening treatment but more in a knowledge of the primary limiting factors of hardenability, then the method of Davenport and Bain[1] may be used. This method involves, (a) the determination of rate of transformation of austenite at constant sub-critical temperatures, and (b) the determination of the nature of the various isothermal products obtained.

Such information, when plotted to show the time required for the initiation and completion of austenite conversion at constant temperatures, yields the so-called S-curve, the significance of which was recognized by its originators, Davenport and Bain.[1] Certainly this technique is too time-consuming for general application, yet its use is justified when the fundamental differences in hardenability are being studied in steels having important differences in composition.

Because of these considerations the hardenability of molybdenum-containing steels was investigated by ascertaining their temperature vs. isothermal-reaction-time curves. The curves for eight molybdenum-bearing SAE steels, one manganese-silicon-molybdenum steel, and one carbon steel are presented here. Ultimately it is desired to report the complete picture of the effect of molybdenum on hardenability, as revealed by this technique.

Apparatus and Experimental Procedure

The metallographic method, as described by Davenport and Bain,[1] was used to follow the course of austenite decomposition at temperatures between 1300 and 650 deg. F. In this temperature range hardness tests were also made to supplement the metallographic method. Between 650 and 400 deg. F. the reaction was studied dilatometrically, using an apparatus designed to measure rapid length changes at elevated temperatures.

The arrangement of apparatus for making the dilatometric tests is shown in Fig. 1. The quenching dilatometer consists of a horizontal bar with a scale and telescope fixed to one end and, mounted on the other end, a device to hold the specimen in a sub-critical or super-critical metal bath while magnifying its expansion. This assembly is supported on a heavy rod that slides in a vertical cylinder to permit quick transfer of the specimen from the super-critical lead bath to the lead-bismuth sub-critical bath.

The means of holding the specimen in the metal baths while recording its change in length is shown in Fig. 2. The specimen is bolted to the rigid right vertical member (as viewed in Fig. 2) and to the left vertical, movable member. The left vertical member, suspended from the main horizontal member by two pairs of flat Elinvar springs, is restricted

to motion in a vertical plane containing the specimen. Fig. 2 shows one pair of these springs held in the shape of an inverted V which further restricts motion of the left vertical member to rotation about an axis through the vertices of the two inverted V springs. The V springs act as flexure members transmitting motion without friction and without back lash. To eliminate friction at the points connecting the specimen and the two vertical members, relative movement is prevented by tightly bolting the three together, forcing this small displacement to take place by flexure at the notches cut near either end of the specimen. The motion due to expansion and contraction of the specimen is then carried with an Elinvar wire from the top of the movable, vertical member to a point on the circumference of a small Stellite mirror. The mirror is held by a third rigid vertical member.

This construction is shown in Fig. 3. A helical spring maintains the Elinvar wire in tension, this same spring serving also to hold the specimen in tension, making it possible to use very thin specimens, *i.e.,* at least as thin as 0.017 in. The vertical mirror support is fixed to the main horizontal member. The mirror rotates about a tungsten suspension wire soldered across the diameter of its case. The mirror support includes adjusting mechanisms for focusing the scale image into the telescope and controlling the tension on the tungsten suspension wire and the tension on the Elinvar wire that carries the motion from the movable vertical member to the lower half of the mirror.

Thus, the motion of expansion and contraction of the specimen is carried to the mirror only by flexure or rigid members, friction and back lash being eliminated. Movement of the mirror is observed in a 5½ power telescope containing an image of a portion of the scale, which image is reflected into the telescope by the mirror. The magnification of movement is principally optical; the total magnification being 297 times. This optical method of magnification being low in inertia has particular advantage when the instrument is being used to record the very fast reactions in the Ar″ region.

The lower portions of the vertical members holding the specimen are subject to large changes in temperature. That they are at right angles to the direction of expansion of the specimen, of course, reduces considerably the effect of their length changes on the position of the mirror. These specimen grips (Fig. 2) are made of 17 per cent chromium stainless steel designed for maximum rigidity, with minimum heat content and maximum surface-to-mass ratio. The cross section of the specimen grips is, therefore, similar to a Greek cross. The three vertical members, the telescope support and the main horizontal member are made of Invar and are cooled by circulating water. The entire instrument is fixed

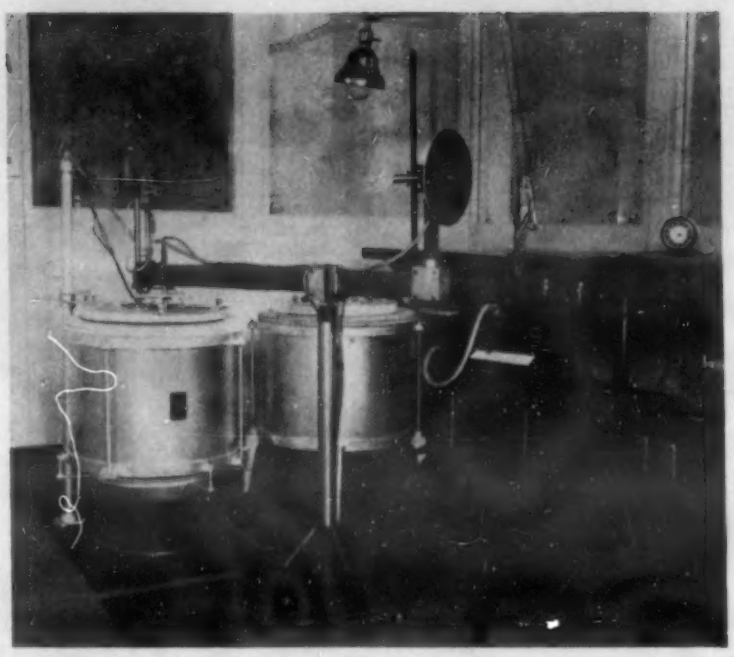
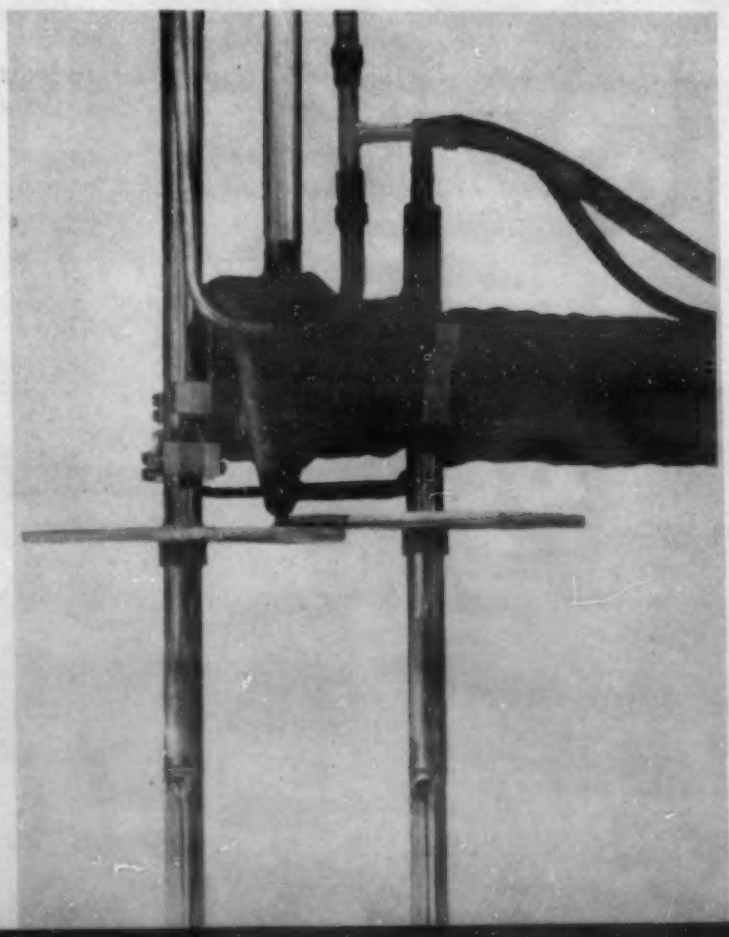


Fig. 1. Arrangement and apparatus for making the dilatometric tests.

to a heavy steel plate which in turn is floated in vibration-dampening rubber supports. The subcritical metal bath is mounted on a standard sales display turntable and during the quenching operation and when taking readings it revolves at 11 r.p.m. The relative motion thus produced between specimen and quenchant aids in obtaining a rapid quench and in maintaining a uniform temperature along the specimen.

At the start of each run where frequent readings are desirable it is customary to use some voice recording instrument which in addition records time simultaneously. When the progress of the austenite

Fig. 2. Means of holding the specimen in the metal baths while recording its change in length.



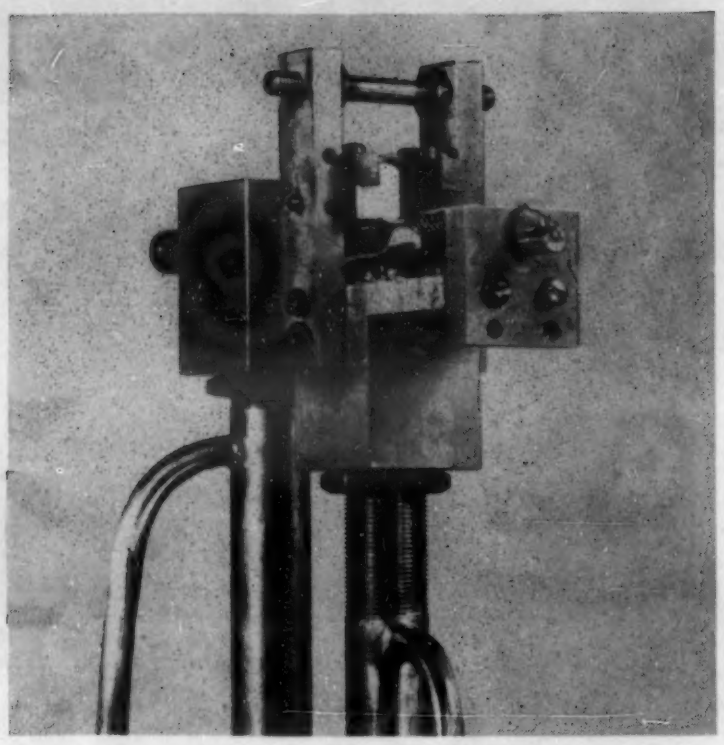


Fig. 3. The mirror is held in a third rigid member.

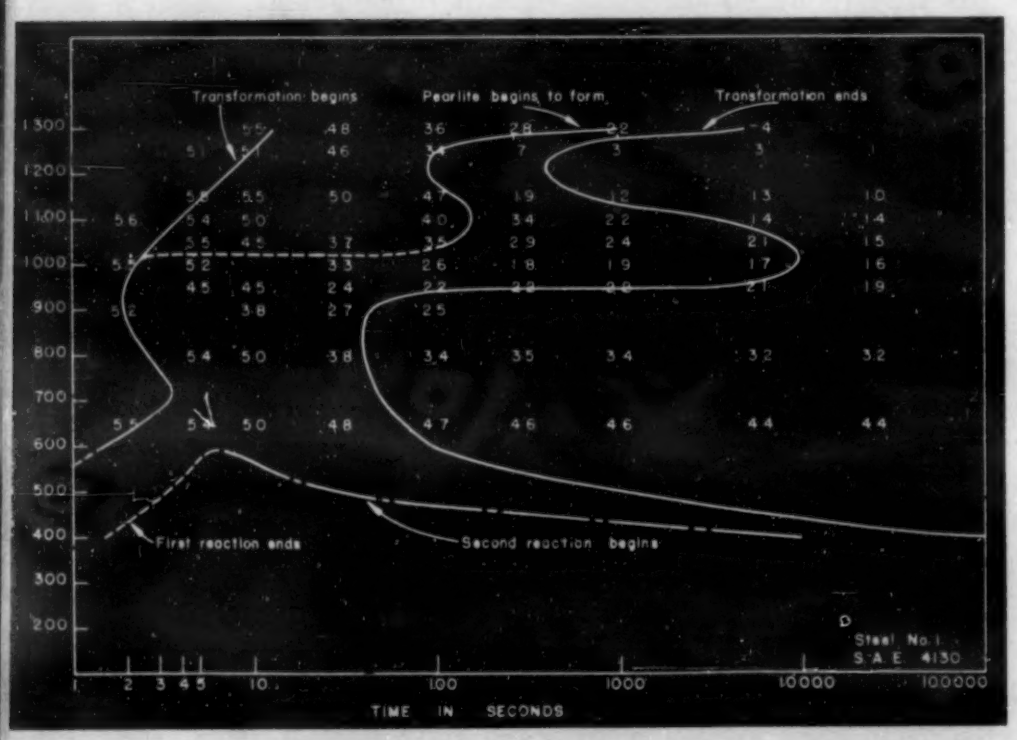


Fig. 4. Time for the start and finish of the austenite decomposition reaction in steel No. 1, SAE 4130. Additional curves, in this and in Figs. 5 to 13 inclusive, are found designating an apparent split in the reaction.

decomposition reaction is too rapid for the observer to follow, the scale readings are recorded by a medium high speed movie camera mounted at the eyepiece of the telescope. The time factor here can be determined by calibrating the speed of the camera.

A brief description of a typical dilatometric test follows:

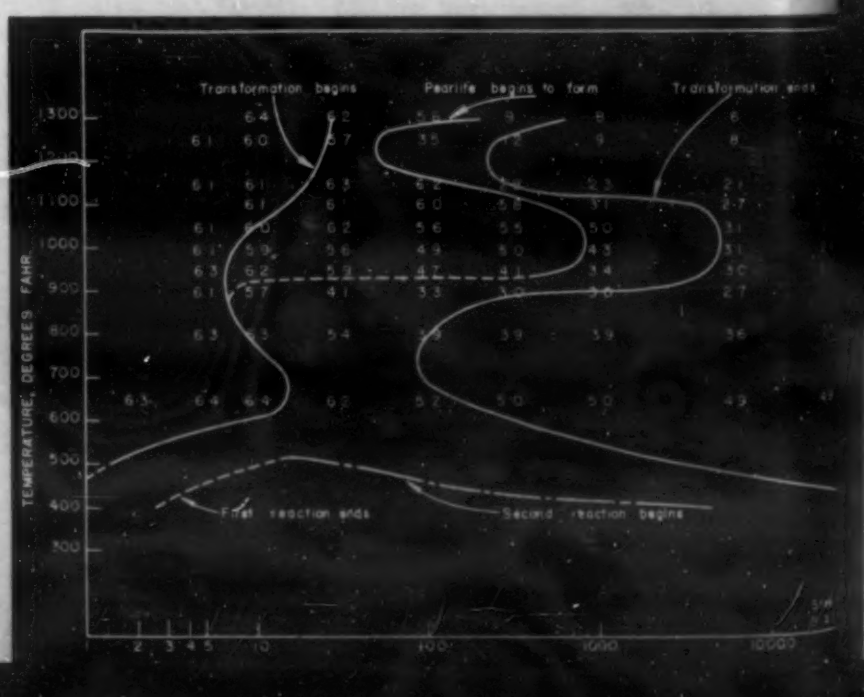
A steel specimen 4 in. by ½ in. by 0.035 in. (For the very fast reactions, specimens 0.017 in. thick are used to increase the speed of quench.) is placed in the grips. The dilatometer is then swung into position for heating the specimen to the solution temperature, and in this position the specimen will be held 2½ in. below the surface of a molten lead bath. After a heating period of 30 mins., the operator swings the specimen from the super-critical lead bath to the sub-critical lead-bismuth bath. This maneuver requires somewhat less than one second. The observer now begins dictating the scale readings and continues to do so until the period of fast reaction is past. Thereafter readings are recorded as required to establish a reliable time vs. dilation curve.

Analyses of the Steels and Preparation of Samples

The analyses of the 10 steels studied are given in the Table. The carbon steel (No. 10) was made in an acid-lined high-frequency induction furnace. The manganese-silicon-molybdenum steel (No. 9) was made in a direct-arc acid electric furnace. The eight SAE steels were obtained from commercial sources, and to exhibit the normal differences experienced in the hardenability of commercial heats of SAE 4140, three steels of this type were selected.

The steels were hot rolled to strips ½ in. wide by 0.075 in. thick. The strips were normalized at 1650 deg. F., annealed one hour at 1500 deg. F., followed by a slow cool to room temperature. From the homogenized strips samples were cut for use in both the metallographic and the dilatometric tests. For the metallographic tests ½ in. square samples ground to 0.055 in. thick were prepared. A small hole in each sample permitted fastening by wire to a stainless steel rod which served as a handle for quenching in the sub-critical bath and in water. For the dilatometer tests samples 4⅜ in. long were ground to 0.035 in. thick. Two holes 0.086 in. dia., 4 in. apart, were drilled in these specimens to permit bolting to the dilatometer. After notching the dilatometer specimens near each end to permit flexing, as noted under the description of the quenching dilatometer, they were drawn one hour at 1200 deg. F. and cooled in the furnace to room temperature. This last heat treatment eliminated stresses due to grinding and prevented the specimen from bending in the dilatometer during transformation.

Fig. 5. Same data as Fig. 4 for steel No. 2, SAE 4140.



Results

The time for the start and finish of the austenite decomposition reaction in the 10 steels is given by the curves in Figs. 4 to 13. On these charts will be found additional curves designating an apparent split in the reaction. This phenomenon will be decribed in detail later. The small numerals on the charts are the room temperature hardnesses (Rockwell C Scale) of water-quenched samples held for the time and at the sub-critical temperature designated by their position on the chart.

Discussion

The hardening process in steel is an extra-equilibrium reaction and before the development of the isothermal transformation technique did not appear amenable to systematic analysis. From the approach to the problem gained through the isothermal technique two useful propositions were induced: (1) the *rate* of transformation of austenite depends on the temperature at which transformation occurs, (2) the *nature* of the product of austenite decomposition depends on the temperature at which transformation occurred. It will be seen that these propositions, applied in conjunction with specific S-curves are useful in the study of the hardenability of alloy steels, and in turn our confidence in their truth is strengthened.

For the 10 steels under discussion, consider first the so-called nose of the S-curve, that zone of minimum austenite stability generally occurring between 850 and 1050 deg. F., also called the Ar′. It is in this region that the lamellar products gradually give place to the harder acicular products as the temperature of transformation is lowered. Since that portion of a given sample of austenitized steel failing to transform on cooling through the Ar′ will transform to martensite in the second region (the Ar″) of rapid austenite decomposition, the position and shape of the nose of the S-curve defines the critical quenching rate of the steel. We may, therefore, use the position and shape of the nose of the S-curves for each of the 10 steels as a basis for rating their hardenabilities. The 10 steels in order of increasing hardenability are given below, and since it will be of interest to compare the data from the S-curves with those obtained from an end-quench test, attention is called to Fig. 14 where the Jominy[2] hardenability curves for these steels are given. The hardenability ratings obtained from inspection of the S-curves are as follows:

No. 10 0.65% carbon	No. 2 SAE 4140
No. 7 SAE 4615	No. 3 SAE 4140
No. 1 SAE 4130	No. 9 Mn-Si-Mo
No. 8 SAE 4640	No. 5 SAE 4150
No. 4 SAE 4140	No. 6 SAE 4340

Some estimation is involved in the above classification since the minimum time for the beginning of transformation at Ar′ must be evaluated with due consideration of the shape of the nose of the S-curve. The grading is quantitative for those steels having curves with similarly shaped noses, but qualitative in two such steels as No. 5 (SAE 4150) and No. 6 (SAE 4340). Since the shapes of the noses of the S-curves vary within such wide limits we have a clue to one of the difficulties in designing a hardenability test that will predict the depth of hardening in given sized rounds. It thus appears that a hardenability test to be strictly accurate should provide a wide variation in over-all cooling time, and in addition, the slopes of the cooling curves in the Ar′ region should vary in the same manner as in the section shape in which the hardenability is to be predicted.

The Ar′ region reveals a further effect of alloys on hardenability through the difference in the time for initiation of austenite transformation and the time for its completion. This difference is a measure of the average rate of reaction in the Ar′ region. Those steels having a beginning curve close, in point

Fig. 6. Same data as Fig. 4 for steel No. 3, SAE 4140.

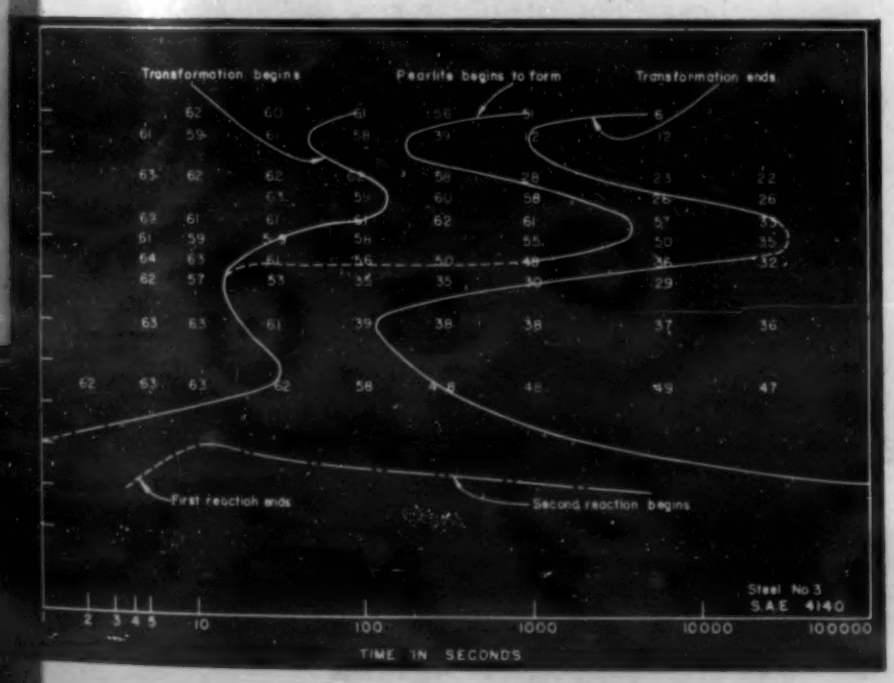
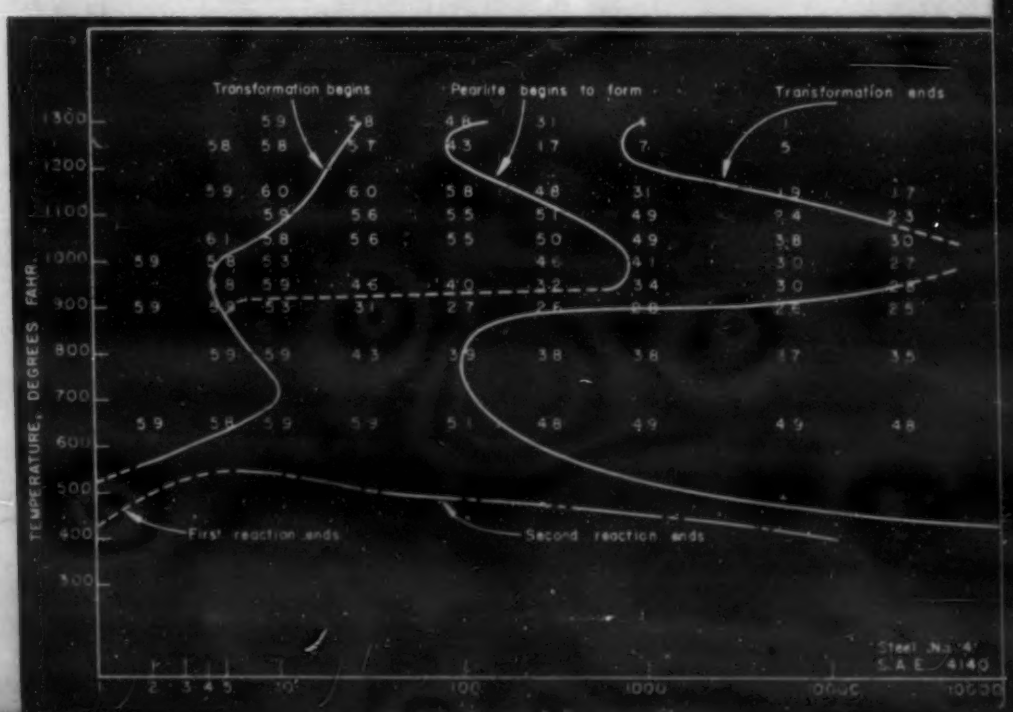


Fig. 7. Same data as Fig. 4 for steel No. 4, SAE 4140.



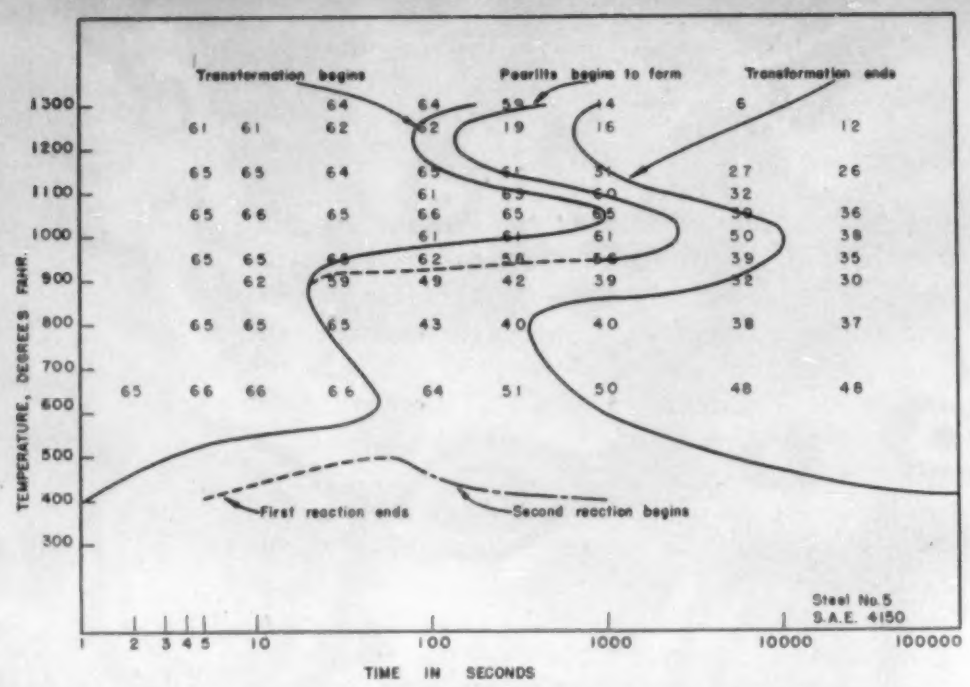


Fig. 8. Same data as Fig. 4 for steel No. 5, SAE 4150.

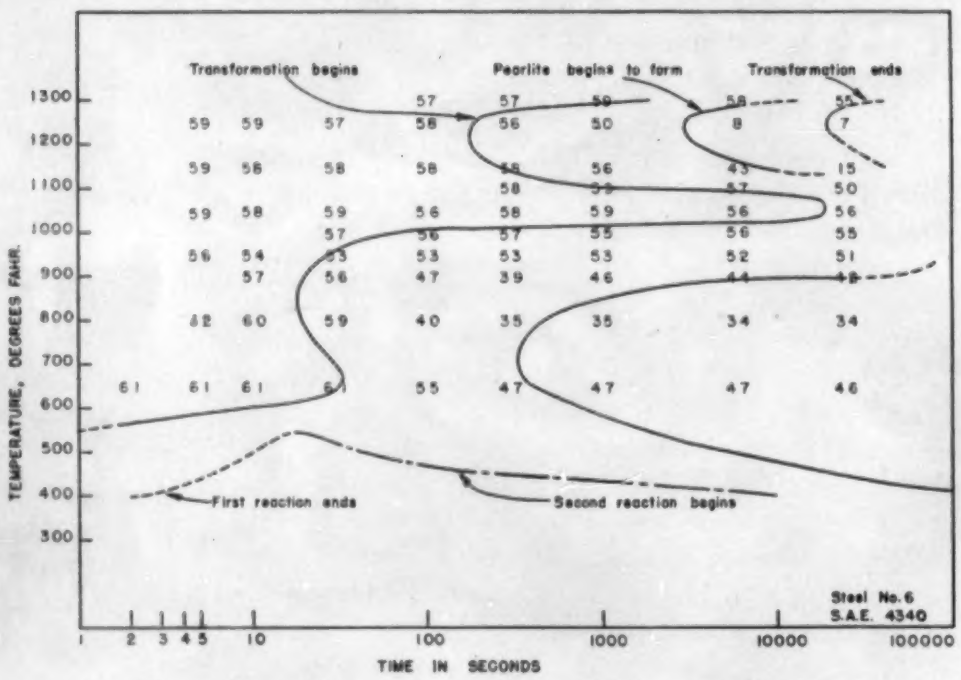


Fig. 9. Same data as Fig. 4 for steel No. 6, SAE 4340.

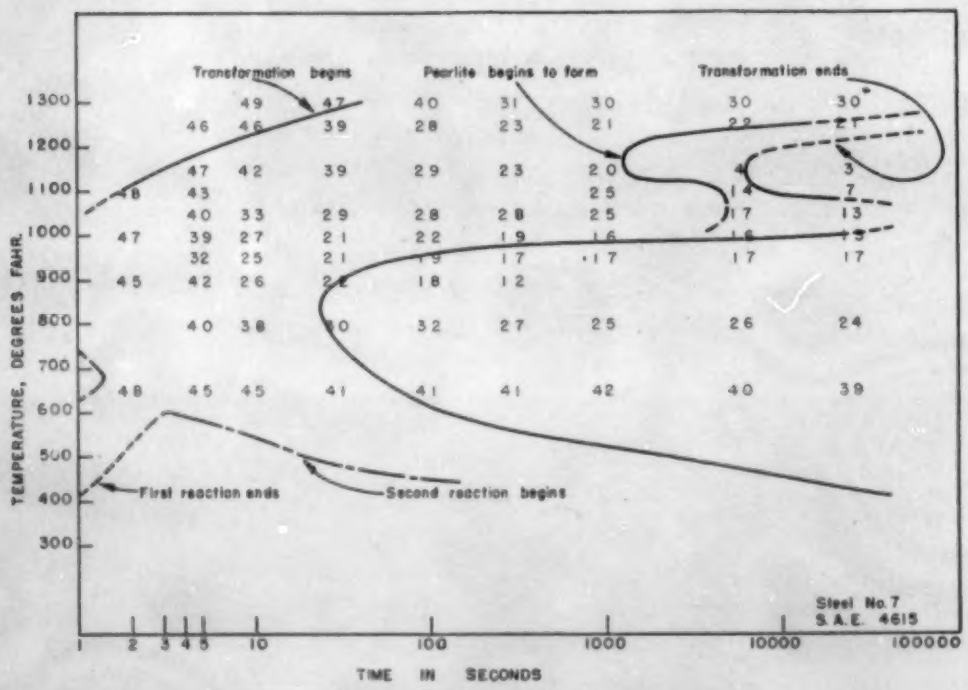


Fig. 10. Same data as Fig. 4 for steel No. 7, SAE 4615.

of time, to the ending curve will evidently exhibit a quick drop in hardness at that depth in a large section where the critical cooling rate just fails to be met. The converse is likewise true. Steels could be classified on the basis of the rate at which their hardness changes from a fully martensitic hardness to the hardness arising from lamellar products. For the present 10 steels this classification would be of academic interest only because of the wide range of carbon content. Nevertheless, the Jominy hardenability curves serve to illustrate the point qualitatively. Notice that the two steels differing most in elapsed time between the beginning and end of austenite conversion at Ar′ are No. 6 (SAE 4340) and No. 10 (0.65% carbon), and that these two steels have the greatest difference in the slopes of their respective Jominy hardenability curves.

Attention is called to the reversal in the course of the S-curves for the nine alloy steels at 1200 deg. F. This unexpected effect of alloys was also observed by Davenport.[3] No interpretation of this reversal is at hand, but certainly it would seem uneconomical to treat those steels isothermally at temperatures included in the bay between the Ar′ and the upper maximum reaction rate occurring at about 1200 deg. F. Drawing to remove retained austenite would likewise be inadvisable at temperatures deep in the bay.

Turning now to the lower portion of the curves, which includes the Ar″, significant differences in the 10 steels are again found. In the alloy steels the region of austenite stability between Ar′ and Ar″ is greatly restricted as compared with the carbon steel. The S-curve in the Ar″ region will determine the temperature at which austenite will transform when the critical quenching rate is exceeded, and, therefore, this portion of the curve determines the maximum hardness attainable in a given steel. If, from the lower portion of the curves, we estimate the temperature at which martensite will form in each steel when all are quenched at a rate exceeding the critical quenching rate of the most shallow hardening steel, we will have an index to the maximum hardness obtainable in each steel. The sequence (This order is generally in agreement with the hardness of each steel at the water-quenched end of the Jominy hardenability bar; see Fig. 14) of the steels set by this criterion will be, in order of decreasing maximum hardness:

Steel	*Carbon, per cent*
No. 10 (0.65% carbon)	0.65
No. 5 (SAE 4150)	0.46
No. 3 (SAE 4140)	0.38
No. 4 (SAE 4140)	0.40
No. 2 (SAE 4140)	0.38
No. 8 (SAE 4640)	0.32
No. 6 (SAE 4340)	0.31
No. 9 (Mn-Si-Mo)	0.29
No. 1 (SAE 4130)	0.28
No. 7 (SAE 4615)	0.17

It is significant that the above arrangement places the steels very nearly in order of decreasing carbon content, indicating that the Ar″ is influenced by carbon content far more than by other alloys. From this point of view it is clear that carbon content is highly important in fixing the maximum hardness obtainable. This is so, not merely for the reason that more and more carbides are provided when the carbon content is increased, but also because the bay of austenite stability between Ar′ and Ar″ is extended to lower and lower temperatures, causing the formation of successively harder acicular products, once the steel is quenched at a rate exceeding the critical quenching rate.

Below 650 deg. F. where the reaction product is wholly acicular the metallographic method becomes gradually less precise and, therefore, in the temperature range 650 to 400 deg. F. the transformation of austenite was followed dilatometrically. This procedure is more difficult than the metallographic, but has the advantage of higher accuracy; sufficiently higher, in fact, that rates of reaction and changes in rates of reaction may be detected in addition to the time of the beginning and ending of the process. Austin and Rickett,[4] in analyzing Davenport and Bain's original dilatometric data at temperatures below 650 deg. F., noted that the dilation vs. time curves varied in form with decreasing temperature and were led to suppose that an unknown factor was affecting the rate of austenite decomposition. They surmised that below a certain temperature the reaction occurred in two stages. The time vs. dilation curves of the present investigation show, similarly, peculiar changes in rates of transformation.

The apparent division of the transformation of austenite into two reactions in the temperature range 650 to 400 deg. F. is best described by presenting typical time vs. dilation curves (shown in Fig. 15) which were obtained on steel No. 9. The shape of the time vs. dilation curve at 650 deg. F. is, as Austin and Rickett have observed, similar to that of population growth curves or of curves of autocatalytic reactions. At 600 deg. F. the form of the time vs. dilation curve begins to deviate from that of an autocatalytic curve, and at 550 deg. F. the curve is further distorted so that it is possible to see that the decomposition of austenite might be proceeding in two steps. At 500 deg. F. the time vs. dilation curve clearly leads one to suspect the presence of separate reactions, the first beginning in less than one second and ending in 5 secs., the second reaction beginning in 35 secs. and ending in about 120,000 secs. At 450 deg. F. the time vs. dilation curve shows the first reaction ending still sooner and the second reaction beginning and ending later; at 400 deg. F. the same trend continues.

To obtain a more accurate measure of the rate of this extremely fast initial reaction, a movie camera

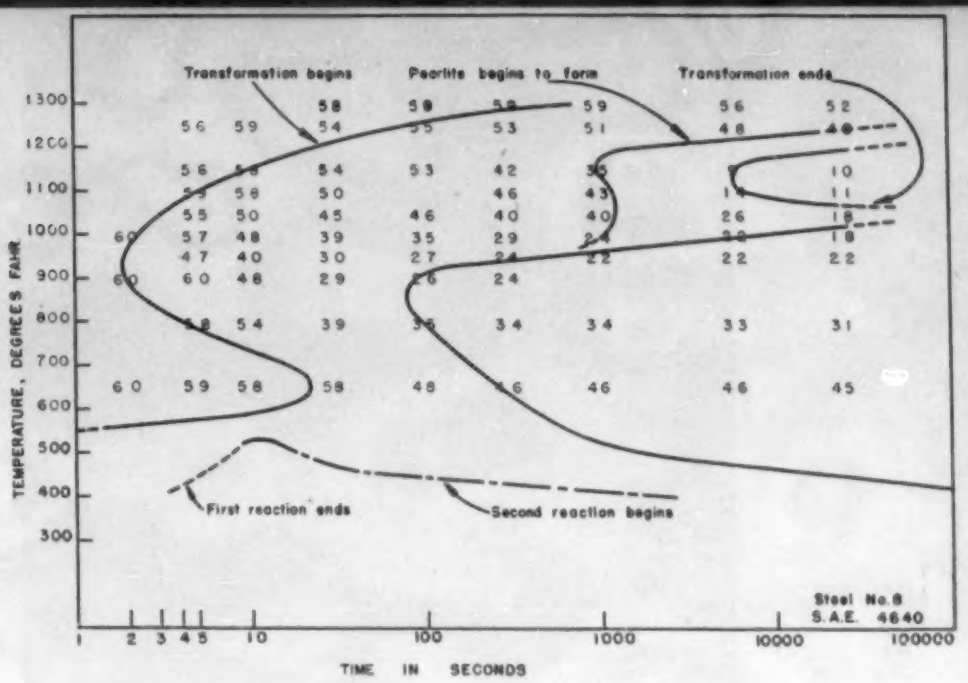


Fig. 11. Same data as Fig. 4 for steel No. 8, SAE 4640.

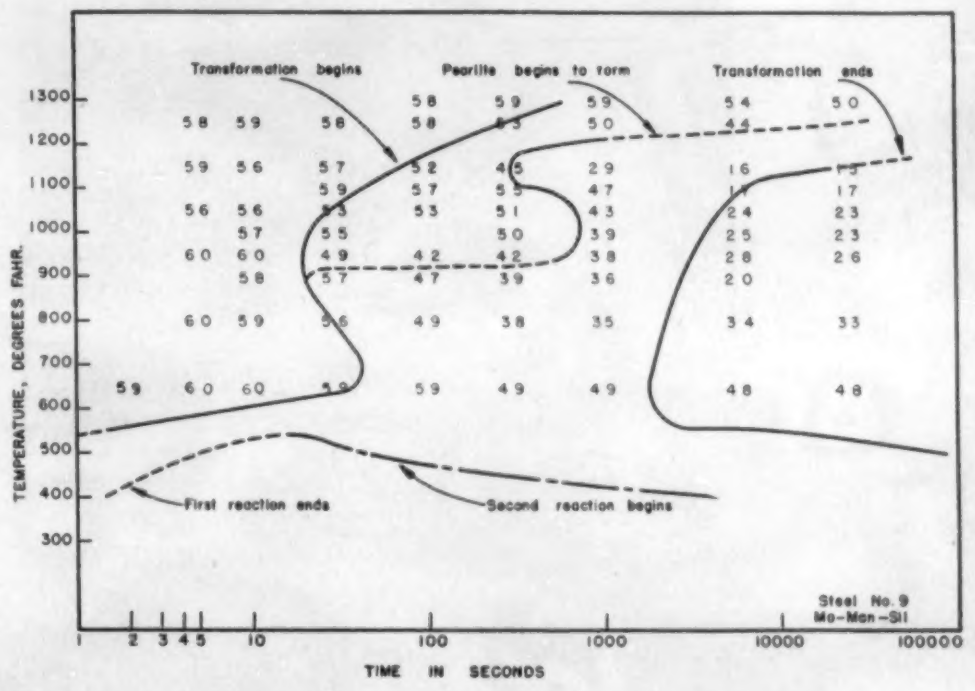


Fig. 12. Same data as Fig. 4 for steel No. 9, Mo-Mn-Si.

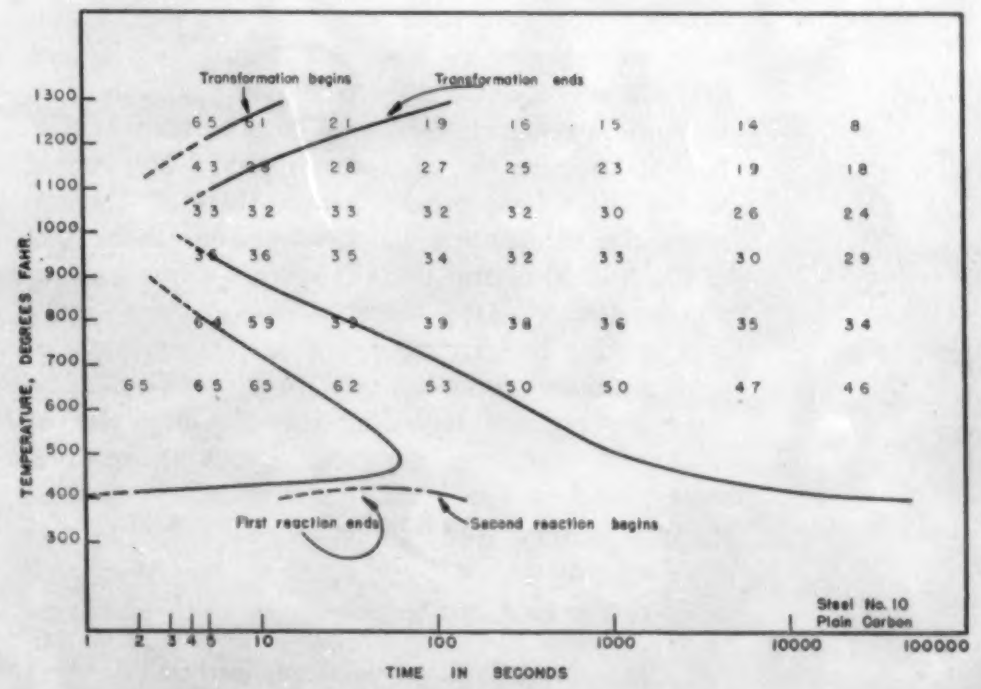


Fig. 13. Same data as Fig. 4 for steel No. 10, plain carbon.

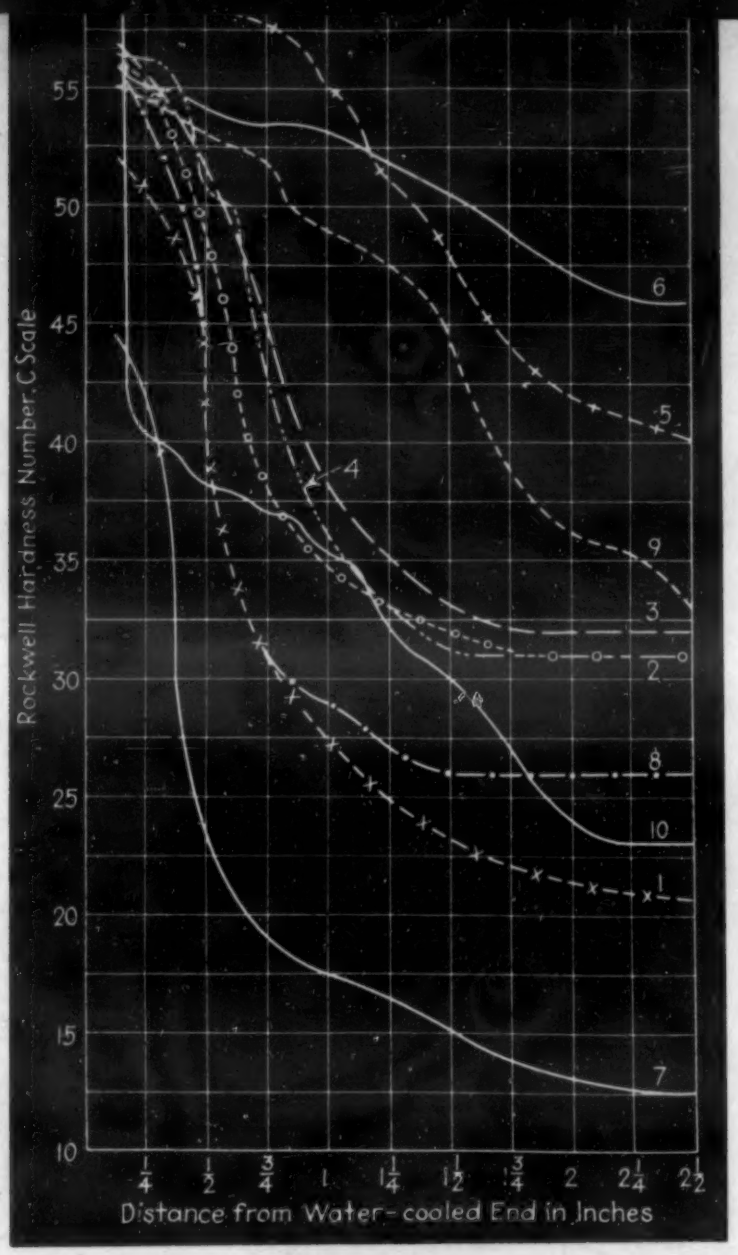


Fig. 14. Jominy-Boegehold hardenability bar curves of 10 steels.

was substituted for the eye of the observer. Fig. 16(a) is a record obtained from SAE 4615 at 600 deg. F. using 64 exposures per second, and shows that the contraction on cooling changed to expansion (due to transformation) within six consecutive exposures, or about 0.1 sec.; the reaction is substantially complete in 2 secs. At 450 deg. F. the same steel begins to transform within two frames or 1/32 sec. after it stops contracting and the first reaction is complete within 1 sec., as seen in Fig. 16(b). Apparently the transformation is so rapid at the latter temperature that the heat of reaction raises the temperature of the specimen above that of the lead bath, and there is again a slight contraction immediately after the first reaction.

Admitting that formal proof for the existence of dual austenite decomposition reactions is lacking, some observations regarding the changing rate of isothermal austenite decomposition will be presented, and to avoid ambiguity reference to these changes will be made in terms of "first reaction" and "second reaction."

1. The lower the temperature at which transformation takes place, the more rapid is the first reaction and the slower the second reaction.
2. As the temperature of transformation is raised, the two reactions approach each other in point of time, until, at a certain temperature which is characteristic for each steel, the two reactions appear to merge.
3. Both reactions cause an expansion, i.e., decrease in density of the steel.
4. As the temperature of transformation is lowered, the proportion of expansion that takes place in the first reaction increases while the proportion of expansion involved in the second reaction decreases.
5. In hypo-eutectoid steels decreasing the carbon content raises the temperature at which transformation first splits (into two reactions) and also raises the temperature at which the first reaction becomes extremely rapid, so rapid that it is practically impossible to cool thin specimens below this critical temperature before the first reaction is complete.
6. A net contraction is never observed during the more or less dormant period between the two reactions.

An explanation of the complicated changes in rates of austenite conversion may be developed qualitatively on the assumption that high internal ferrostatic pressure will arise from the concomitant volume changes. The effect of the pressure variable on the rate of isothermal austenite decomposition has not been measured but the direction of its effect has been predicted by the Le Chatelier principle.[5] If pressure has an appreciable effect on the rate of austenite decomposition it will be in the direction of retarding the rate with increasing pressures, since all products of austenite conversion are more voluminous than the parent material. At relatively high temperatures volume changes occurring randomly within austenite may not develop ferro-static pressures of a magnitude sufficient to decrease the rate of transformation of the remaining austenite and the process will proceed as a simple reaction. However, as the temperature of transformation is lowered the volume changes will be less readily accommodated by virtue of the greater strength and higher modulus of cubic compressibility of the already transformed material, and as a consequence higher internal pressures could be produced. On further lowering of the transformation temperature a pressure may eventually be attained great enough to practically stop transformation pending relief of stress by some time-consuming mechanism such as diffusion.

Obviously, if this hypothesis be correct the transformation at Ar″ should not be considered as occurring in two steps, and the true end of transformation would be placed at the end of the second reaction. But the hardening process appears for all practical purposes to be complete at the end of the first reaction, and this point, therefore, is really more useful. Accordingly the curves for the 10 steels have been

Fig. 15. Time-dilation curves for steel No. 9.

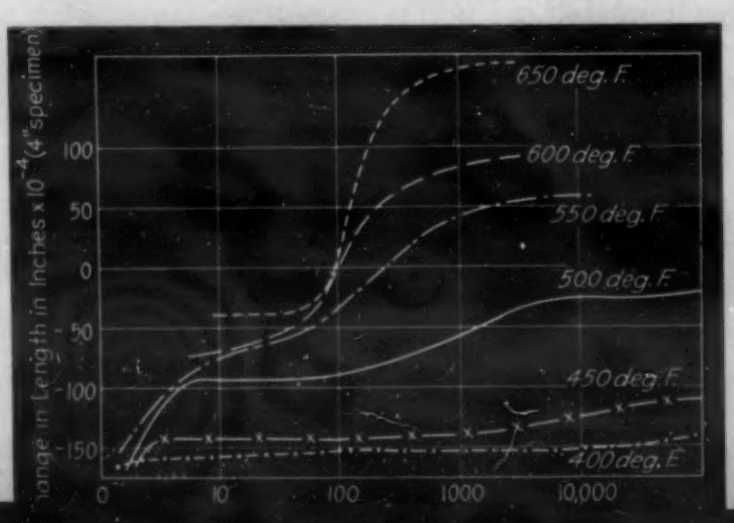


TABLE OF ANALYSES OF THE 10 STEELS STUDIED

Type	4130	4140	4140	4140	4150	4340	4615	4640	Manganese-Silicon-Molybdenum	Carbon
No.	1	2	3	4	5	6	7	8	9	10
C, %	0.28	0.38	0.38	0.40	0.46	0.31*	0.17	0.32*	0.29	0.65
Mn, %	0.65	0.67	0.82	0.68	0.77	0.66	0.57	0.74	1.70	0.39
Si, %	0.19	0.27	0.23	0.20	0.28	0.28	0.26	0.31	1.11	0.19
P, %	0.016	0.016	0.018	0.016	0.016	0.014	0.017	0.015	0.017	0.011
S, %	0.023	0.020	0.022	0.032	0.025	0.018	0.018	0.014	0.014	0.023
Cr, %	0.66	1.01	1.02	1.00	1.06	0.72	0.13	0.12	0.01	0.16
Ni, %	0.16	0.08	0.29	0.21	0.15	1.67	1.73	1.70	0.10	0.19
Mo, %	0.22	0.18	0.20	0.22	0.22	0.34	0.26	0.23	0.13	0.03

* The heat analyses given by the supplier indicated that these steels were within SAE specifications. The above analyses are those determined on the actual bars used.

drawn to show the beginning of transformation, the end of the first (rapid) reaction, the beginning of the second reaction and finally, the end of transformation.

Summary and Conclusions

The hardenabilities of eight molybdenum-bearing SAE steels, one manganese-silicon-molybdenum steel, and one carbon steel have been studied by obtaining their temperature vs. isothermal-reaction-time curves (*i.e.* S-curves).

The shapes of the alloy steel curves are significantly different from those for carbon steels. Each of the nine alloy steels has a more or less prominent reversal in its temperature vs. isothermal-reaction-time curve below about 1200 deg. F. The effect of alloys in reducing the critical quenching rate is clearly indicated by the shifting of the nose toward greater time. This latter effect, however, was expected. To find that the effect of alloys (such as Ni, Cr, Mo) on the lower portion of the curve is relatively small and greatly overshadowed by the effect of carbon was not expected. The effect of increasing carbon in expanding the region of austenite stability below 900 deg. F. gives a more definite understanding of the varied response of low, medium and high carbon steels to hardening.

Evidently the upper portion of the curve (above 900 deg. F.) is modified most readily by alloys such as Mn, Cr, Ni, Mo, and V, whereas the lower portion (where acicular products occur) may be controlled best by carbon. This logically directs attention to the possibility of selecting steels with an alloy content sufficient to reduce the critical cooling rate to fit the section size (or heat-treating practice) and with a carbon content that will enforce transformation to an acicular product of the desired hardness when treated by conventional liquid or air quenches.

If steels No. 2 (4140), No. 3 (4140), No. 4 (4140), No. 6 (4340), No. 8 (4640) are quenched from above the critical temperature in a medium that cools at a rate in excess of the critical cooling rate, their temperature vs. isothermal-reaction-time curves show that they will transform in the range 450 to 550 deg. F. The product of transformation

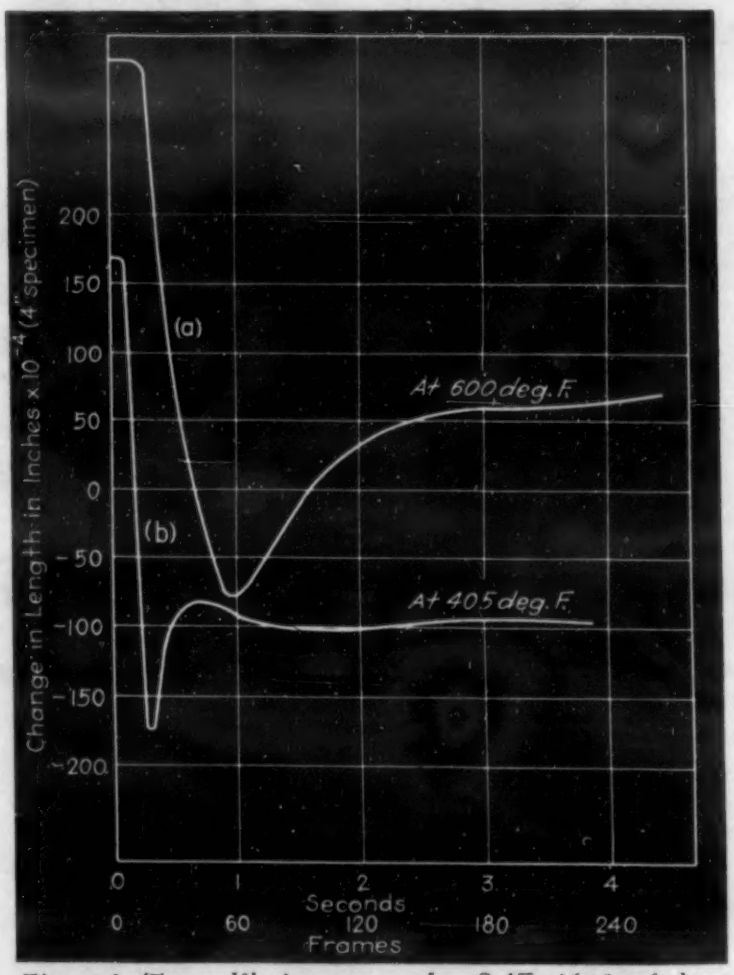


Fig. 16. Time-dilation curve for SAE 4615; (a) at 600 deg. F. and (b) at 405 deg. F.

in this temperature range is not one of maximum hardness but does have an excellent combination of hardness and ductility.

The temperature vs. isothermal-reaction-time curve is a useful supplement to the equilibrium diagram, for it defines a system that is not in equilibrium, a status prevailing in ferrous metallurgy far more frequently than the usually hypothetical equilibrium condition.

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[2] W. E. Jominy & A. L. Boegehold. "A Hardenability Test for Carburizing Steel." *Trans. Am. Soc. Metals*, vol. 26, 1938, pages 574-599.

[3] E. S. Davenport. Campbell Memorial Lecture, October, 1939.

[4] J. B. Austin & R. L. Rickett. "Kinetics of the Decomposition of Austenite at Constant Temperature." *Trans. Am. Inst. Mining Met. Engrs.*, vol. 135, Iron & Steel Div., 1939, pages 396-415.

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"18 and 8"

An all stainless steel airplane fabricated by Fleetwings, Inc., Bristol, Pa.

Although engineers and designers have finally accepted as fact the unfortunate circumstance that "18 and 8" cannot be universally applied to the solution of every corrosion problem, greater understanding is still required of its limiting characteristics. In many cases such knowledge would not only prevent occasional misapplication, but, more important, would permit redesign on such a basis that the real advantages of this highly useful alloy could be fully and more widely enjoyed. The "18 and 8" and related steels have before them a truly brilliant future, but this cannot be attained until users understand their peculiarities and available methods of circumventing them.

This article discusses the characteristics—good and bad—of the "18 and 8" steels in straightforward fashion. Those factors that affect design, whether for corrosion resistance or engineering properties, are clearly explained, and much information on the employment of modified compositions for special purposes is given. The article will have distinct value as a practical aid to the wider and more intelligent use of these steels.—The Editors.

TWENTY-FIVE YEARS HAVE ELAPSED since the first of the series of steels that have come to be known as "stainless" was introduced to commerce in the form of cutlery, and about 15 yrs. since the most important group of this series—the austenitic chromium-nickel steels—was first produced commercially in the United States.

The importance of these steels need hardly be emphasized. They are now well known, and have demonstrated their usefulness in many diversified applications. In many industries they have become indispensable; in others, possibly because of overzealous efforts to build up sales, and to insufficient preliminary experimental work, costly failures have resulted. The stainless steels are not panaceas but, as with other products, have their logical and proper fields of usefulness.

History

In this article, it is not intended to review the various specific applications for which stainless steels have been found useful, but to discuss in a general

and Related Stainless Steels—I

by WALTER M. MITCHELL

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way those metallurgical characteristics of the commercially most important group—the austenitic "18 and 8" and its relations—that are most interesting from the service standpoint.

The introduction of the austenitic stainless steels is to be credited to Strauss and Maurer of the Fried. Krupp, A. G. of Essen, Germany. They began their investigation in 1909, but it was not until some 11 yrs. later that the complete announcement was made. They found that the iron-chromium-nickel combination had distinct advantages. Transformation ranges were lowered by the addition of nickel with the result that the alloy remained austenitic at room temperature. And as nickel possessed good corrosion resistance of its own, this was imparted to the alloy, and thus, the new alloy showed a wider range of corrosion resistance than the analogous plain chromium steel; and, further, possessed improved mechanical properties.

The curve obtained by Strauss and Maurer for the relative proportions of chromium and nickel required to produce an austenitic steel showed about 12 per cent Ni with 8 per cent Cr, and 5 per cent Ni with 20 per cent Cr. Later investigations by Bain and Griffiths showed that, as the alloys are ordinarily produced, a higher nickel content is necessary for a stable austenitic steel; namely, 17 per cent Ni with 8 per cent Cr, and 7 per cent Ni with 20 per cent Cr. The boundary line of the austenitic area of the constitutional diagram is not well defined, and its position will be altered by the presence of other elements in the alloy, especially carbon and nitrogen; and even at this time we are still uncertain regarding the complete influence of other elements although they may be present in small percentages only. It will thus be noted that the commercially produced "18 and 8" stainless steel is to be considered as a "marginal" type of alloy.

As a result of their experiments the Krupp firm brought out the first austenitic steel of this type with the symbol "V2A", with approximate composition 20 per cent Cr, 7 per cent Ni, and 0.2 per cent C. By about the end of 1923 these steels were introduced in England by Brown-Bailey's Steel Works, Ltd., and by Thos. Firth and Sons, Ltd. They appear to have been first produced in the United States about 3 yrs. later.

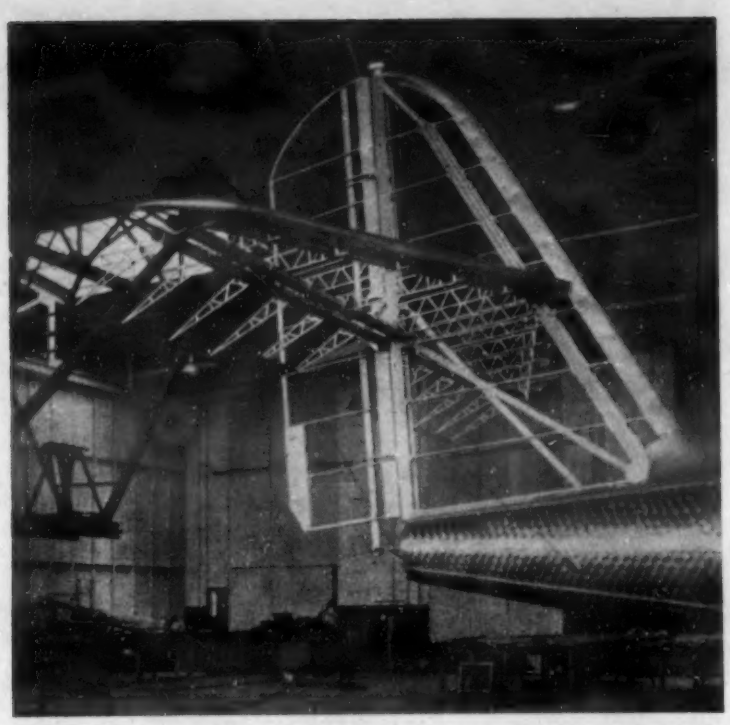
The original composition was somewhat modified with introduction into England and the United States. The Brown-Bailey Co. produced a steel with 15-16 per cent Cr and 10-11 per cent Ni under the trade name "Anka," while Thos. Firth and Sons, Ltd., as a result of Dr. Hatfield's suggestions, adopted the composition 18 per cent Cr and 8 per cent Ni, to which the name "Staybrite" was given. The steel first produced in the United States seems to have been copied directly from the Staybrite analysis, without any endeavor being made to determine which analysis would be best for a general purpose steel.

The composition ranges have since been rather widely extended, so there is now available a series of steels of the iron-chromium-nickel combination varying from "16 and 6" through "17 and 7", "18 and 8", and "19 and 9" to "20 and 10" and higher, all of which resemble the original "18 and 8" in certain respects. The lower alloy steels have resulted from the demand for a lower cost material that would be sufficiently tarnish-resisting for the milder applications, while the higher alloy steels, such as "25 and 12" and "25 and 20", were developed through requirements for greater corrosion resistance and high temperature usage.

General Properties

Generally the austenitic steels have a single phase structure and show no critical transformations in the ordinary sense of the term. In consequence, the physical properties of "18 and 8" depend mainly on its composition and the amount of cold work it may have received. Considering first and very briefly variations in composition, the effect of increased carbon is increased strength, particularly the proportional limit, and increased hardness. Ductility, as measured by elongation and reduction of area, is lowered. Increase in chromium, other elements remaining constant, raises tensile strength and slightly lowers ductility. Increase in nickel, within limits commercially used, stabilizes austenite with respect to its transformation into martensite and ferrite, lowers tensile strength and hardness, but increases yield point slightly. One marked and useful effect of increasing nickel, resulting from its stabilizing effect on austenite, is a distinct decrease in hardening on cold working.

Since these steels show no phase change on heating, recrystallization does not occur except after mechanical disturbance of the prevailing structure, as by cold work. Thus, it is not possible to increase hardness, as with carbon steels, by any process of heat treatment, but only by mechanical working in



Some details of construction of a stainless steel airplane made by Fleetwings, Inc., Bristol, Pa.

the cold. But when once work hardened the steels may be softened by heating. Again, if the steel possesses a coarse structure, it may be refined only by mechanical breakdown in hot or cold rolling, followed in the latter case by a suitable heat treatment. It is not refinable by heat treatment alone, but may be made coarsely crystalline by overheating.

To insure homogeneity of structure the austenitic stainless steels must be cooled rapidly from a high temperature. After such cooling they will consist entirely of austenite, be non-magnetic, and exceedingly tough and ductile. They will have a low yield point, and one, moreover, which is not well defined. Its value will run, as ordinarily estimated in tensile tests, from 35,000 to 40,000 lbs. per sq. in. Tensile strength varies with the composition, and with the temperature from which the steel has been cooled, but is generally in the range 80,000 to 100,000 lbs. per sq. in.

The fact that these steels show very high values for reduction of area and elongation in tensile tests, together with their low yield point, is indicative of great capacity for undergoing deformation when cold worked. This is one of their important advantages and has facilitated extending usage in various fields. But it should be borne in mind that high tensile strength, with low yield point, indicates that considerable hardening takes place from cold work during the test. The behavior of test specimens undergoing tensile tests would indicate that when the austenitic chromium-nickel steels are deformed cold, as in a deep drawing operation, they should flow very easily at first, fully as easily as carbon steel, but as deformation continues they should stiffen up more rapidly than other metals, so that a much higher strength will be evidenced at final fracture—and such is actually found to be the case.

In the fully annealed condition these steels have a very low proportional limit—running around 18,000 to 25,000 lbs. per sq. in. In some cases the curve of an accurate stress-strain diagram will show no straight portion whatever and be curved from the origin. Reported values for the modulus of elasticity will vary, according to the degree of cold work, values from 25,000,000 to 29,000,000 having been found.

Cold-Worked Material

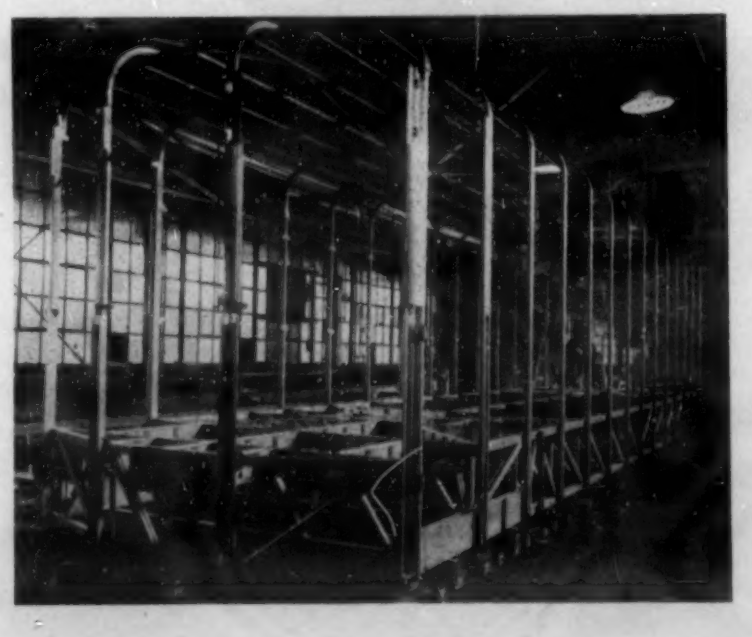
As the commercially produced "18 and 8" steel is located in the margin of the austenitic area there will be a tendency to break down to martensite on cold working. This produces severe hardening, as already mentioned, and is accompanied by a slight increase in magnetic properties, indicating the formation of at least some ferrite, as much as 9 per cent of ferrite by volume having been found by magnetic tests after 50 per cent cold reduction.

Figures on cold-worked material in various forms are illustrative of this. The following shows the effect on various properties as obtained in reduction of a 1-in. round bar to ¾ in. round in four successive passes without intermediate annealing. Composition—0.07 C, 0.34 Mn, 0.40 Si, 17.98 Cr, 8.45 Ni:

Dia. in.	*Tensile Strength lbs. per sq. in.*	*Yield Point lbs. per sq. in.*	*Elong. in 2 in. per cent*	*Red. Area per cent*	*Brinell*	*Izod*
1.0 (as rolled)	104,000	54,000	48.0	71.0	170	110
0.925	143,000	118,000	29.5	61.0	286	88
0.875	163,000	133,000	21.5	58.5	375	52
0.815	199,000	165,000	13.0	50.6	418	26
0.750	227,000	200,300	11.0	44.0	444	17

Similar cold drawing operations on smaller sized rounds have produced very high tensile strength as shown in the following, where the final result of eight successive draws without annealing is given. Compo-

Some details of the construction of a Budd stainless steel train.



A modern stainless steel streamlined train, built by Edward G. Budd Mfg. Co., Philadelphia.

sition— 0.08 C, 0.42 Mn, 0.45 Si, 17.17 Cr, 8.88 Ni:

Dia. in.	*Tensile Strength lbs. per sq. in.*	*Yield Point lbs. per sq. in.*	*Elong. in 2 in. per cent*	*Rockwell*
0.218 (annealed)	84,400	34,800	65.0	77B
0.062	333,500	——	2.0	42C

The effects of severe cold reduction in cold rolling of strip for high tensile applications is also interesting and values are given in the following table. Composition— 0.10 C, 0.34 Mn, 0.40 Si, 17.86 Cr, 7.68 Ni:

Reduction per cent	*Tensile Strength lbs. per sq. in.*	*Elong. in 2 in. per cent*	*Brinell (equivalent)*
0 (annealed)	85,000	65.0	165
10	120,000	40.0	238
20	145,000	28.1	280
30	165,200	20.0	310
40	190,100	15.7	330
50	210,300	8.2	380

Design Factors

Cold rolled "18 and 8" strip has been developed into a most important structural material for transportation equipment. The high tensile strength of this material makes great reduction in dead weight possible, and it is now well established for construction of railroad equipment, airplanes, ship structures, etc. Methods of fabrication—improved spot welding processes—have been developed that are low in cost, highly efficient, and thoroughly dependable. High tensile "18 and 8" does not require heat treatment, nor protection from rusting, and, notwithstanding its somewhat higher original cost, substantial economies in operating costs of railroad equipment are now fully recognized.

For most efficient use revision of design in accordance with the unique characteristics of the metal is absolutely necessary. Without due consideration of this little can be gained. The question of permissible stresses has required most careful consideration, and a word or two on this subject will not be out of order. An excellent discussion of the whole subject will be found in a paper by F. Flader in *Trans. Amer. Soc. Mechanical Engrs.* for May 1934.

Flader mentions the difficulties in the use of "18 and 8" as a structural material because of the absence of a definite yield point, and suggests the selection of an artificial yield point at which the stress-strain curve deviates a definite amount from the straight line of Hooke's Law. The attempt is made to define a value for this yield point so that when structures are designed with use of this value the design load will be sustained without permanent set of any of the members of the structure. Flader defines such a "yield point" as that unit stress under which a test specimen will show an extension of 0.002 in. per in. in excess of that computed from the modulus of elas-

ticity by the formula,

Unit Stress = Mod. of Elasticity X Unit Deformation.

From reliable data a minimum yield point of 140,000 lbs. per sq. in. is obtained for hard cold-rolled "18 and 8". Flader advises that this value may be used in design work, and is believed conservative enough to allow for variations in material, and also for discrepancies between test results and actual failing stresses in built up structures.

Some of the difficulties noted have been overcome through the recent development of a low temperature aging treatment for cold worked material which substantially improves elastic properties. This comprises heating the metal to about 400 deg. F., holding for a sufficient time and cooling in air. This treatment raises proportional limit and yield point without impairing tensile strength, ductility or corrosion resistance. This is an important development, and should result in an increasing use of cold rolled "18 and 8" for structural applications.

It has been found from experience that in the choice of chromium-nickel austenitic steels for high strength structural purposes slight variations in composition have considerable effect on the physical properties. High nickel, as indicated previously, is not desirable as it necessitates greater cold reduction to obtain a given tensile strength and is accompanied by greatly lessened ductility. Lower chromium and lower nickel, especially the latter, work hardens more rapidly, and provides the necessary strength with less reduction, and with greater ductility. The most satisfactory composition, from the point of view of strength, thus far appears to lie in the narrow range 17-18 per cent Cr., with 7-8 per cent Ni, and 0.10-0.12 per cent C.

(To be continued)

Silver in Stainless Steel

At the annual Exposition of Chemical Industries in New York, Dec. 4 to 9, The Chemical Foundation, Inc., in its booth, displayed for the first time "Silver Stainless Steel," both as castings and in sheet form. The display created wide interest. For the benefit of readers of METALS AND ALLOYS we have obtained from Raymond J. Norton of the Chemical Foundation the following preliminary account of the development of this new product and its claimed properties:

This new type of stainless steel has been developed primarily to resist pit corrosion but, in addition to this attribute, presents other striking characteristics, such as free machinability, low work hardening, increased heat conductivity and an ability to take a high polish.

Its Development

The new steel was developed as a result of a research program sponsored by The Chemical Foundation Inc., and carried out by a group of scientists at the Massachusetts Institute of Technology. Their problem was to investigate the phenomenon known as pit corrosion, to determine its causes, and if possible to provide a cure.

Pit corrosion is a special and insidious form of corrosion. It occurs in saline environment, notably in sea water, initiates at a localized portion of the exposed surface of the steel and then progresses substantially autocatalytically directly into the body of the steel in the form of a pit or cavity. Even such effective corrosion resistant steels as 18 and 8 have not been able to withstand the ravages of this form of destructive attack.

It was determined, among other things, that the development of the pit involved the dissolution of metal in the steel by reason of the reaction of chlorine of the sea water with metal components of the steel resulting in soluble corrosion products, *i.e.* the soluble chlorides of iron, nickel and chromium. As the action progressed these soluble products leached away as formed permitting a continuance of the attack. It was discovered that if silver (an insoluble chloride-forming element) was added to, say an 18 and 8 stainless and under such circumstances that it was finely and homogeneously dispersed in the alloy, the steel could be rendered inherently resistant to pit corrosion. The mechanism of the protection involves the formation of the insoluble silver chloride which serves as a protective film against further attack.

Silver Stainless As Castings

The Lebanon Steel Foundry, Lebanon, Pa., at an early date, became keenly interested in the possibilities of this steel and, in collaboration with the Massachusetts Institute of Technology and the Chemical Foundation, conducted an investigation to determine its value as a truly commercial alloy. After a thorough investigation it was established that the new steel possessed many improved characteristics which admirably fitted it for employment in the arts. These characteristics are the more striking when it is considered that they are produced by the addition of but minor amounts of silver, *i.e.* from approximately 0.1 to 0.3 per cent or more. In these investigations The Eastern Rolling Mill Co., Baltimore, Md., collaborated. This company produced rolled sheets of the new steel. The work carried on by The Eastern Rolling Mill Co. clearly demonstrates that the new steel may be produced in sheet form as readily as 18 and 8.

This new silver steel in addition to the known characteristics of 18 and 8 possesses the following advantages:

1. Resistance to pit corrosion
2. Improved machinability
3. Diminished work hardening
4. Increased thermal conductivity
5. Ability to take a high polish

The improved characteristics of the steel open up a wide field of use particularly in those technological fields

Table of Properties of the Various Stainless Steels

Type of Steel	Elastic Limit Lbs. Per Sq. In.	Ultimate Tensile Strength Lbs. Per Sq. In.	Elongation Per Cent	Red. Per Cent	Chemical Analysis						
					Cr	Ni	C	Si	Mn	Ag	Mo
18-8	38,320	76,160	55.1	65.2	20.22	9.23	0.06	1.25	0.59	...	...
18-8 Ag	36,875	76,675	59.3	68.2	19.47	9.51	0.07	1.22	0.76	0.26	...
18-8 Mo	52,360	88,850	43.7	68.1	20.71	9.76	0.06	1.24	0.67	...	2.93
18-8 MoAg	51,750	87,450	45.2	69.1	20.12	9.47	0.06	1.21	0.71	0.28	3.02

where such factors as pitting, deep drawing, high thermal conductivity and the like are problems.

Composition and Physical Properties

The Lebanon Steel Foundry has been producing castings of the new steel in two general types of analyses, namely silver 18 and 8 and silver-molybdenum 18 and 8. The physical characteristics of the new products can be appreciated by direct comparison with ordinary 18 and 8. The Table represents typical average properties of 18 and 8 as compared to 18 and 8 silver and 18 and 8 silver-molybdenum in the form of castings.

As Forgings

The new steel forges readily. The following are indicative of the physical properties of forged material. The analysis of this forging was: Cr 18.83, Ni 9.59, C .09, Si 1.03, Mn .56, Ag .21.

Brinell hardness taken as forged, gave the following values:

207 192 179 163

Values taken as forged and quenched into H_2O at 1950 deg. F. are as follows:

163 163 163

The physical properties as forged are:

Yield	Ultimate	% Red.	% Elong.
53,000	92,500	72.7	55.0

As forged and quenched into H_2O at 1950 deg. F.:

Yield	Ultimate	% Red.	% Elong.
53,500	92,250	69.3	57.0

The new steel is believed to be a notable addition to the corrosion resistant steels and is expected to take its place as the aristocrat of the line possessing as it does all of the worthy attributes of 18 and 8 and in addition other valuable properties.

Technique Involved

The production of the new steel involves a special technique. If silver, in any of its common forms, is attempted to be introduced directly in an 18 and 8 alloy under the usual melting temperatures employed in the industry, it will largely volatilize and be lost. In order to secure the full advantages of the new product, it must be introduced in such a manner that the silver is finely divided and homogeneously dispersed through the ultimate alloy. In order to secure this, silver is first combined with nickel in the form of a master alloy and this master alloy is used as the addition agent. If the silver is properly introduced it will be found in stable form in the ultimate alloy. Furthermore when the proper technique is employed the initial 18 and 8 silver alloy may be reheated and repoured without any substantial loss of silver or in other words the silver 18 and 8 scrap may be used in production.

The form which the silver takes in the alloy is most interesting and, as it happens, such as to add materially to the practical value of the material. Microscopic spheroids of the silver are found throughout, both within the granular structure itself and between the grains.

Licenses under these patents will be available to American industry under three classifications covering casters, melters, and converters.

A Chuckle

"Austempering of S. A. E. Alloy Steels Sometimes Miraculous"

We can't help crudely paraphrasing the title of the article by Payson and Hodapp in the April 1939 issue of *Metal Progress,* after reading an abstract of the article appearing on page 139 of the current (Autumn) issue of our British contemporary, *Metal Treatment.* In the abstractor's (or his printer's) words:

> "it (the steel) will remain austenitic for a short period, and then transform directly to a feathery circular (*sic*) structure (Bainite) when held for the required time at the temperature of the bath. Steel having this structure is *harder* than if it had been quenched and tempered to *the same hardness* by the conventional procedure". (Guess whose italics!)

This extremely rare metallurgical phenomenon has been either modestly or carelessly overlooked by Bain, Davenport, and Legge in their writings on this process. More seriously, though, the rest of the abstract completely reversed the results as published by Payson and Hodapp. The abstractor states that "austempering is definitely better than oil-quenching and tempering when a hardness less than that represented by Rockwell C 44 is required. . . . When greater hardnesses are required . . . the conventional oil quench and tempering treatments appear to give greater toughness." The article as it appeared in *Metal Progress* showed just the opposite, that austempering generally gave greater toughness at the higher hardnesses.

This can probably truthfully be blamed on the stress of war conditions in England, for *Metal Treatment* has been commendably free of such causes for amusement in the past. —F.P.P.

Properties and Machinability

by T. J. DOLAN and B. R. PRICE

Assistant Professor of Theoretical and Applied Mechanics, and former student, respectively, University of Illinois, Urbana, Ill.

Recent articles in this and other magazines have indicated the attractive possibilities in the use of the new lead-bearing open-hearth steels, with their claimed combination of undamaged physical properties and greatly improved machinability because of the presence of small amounts of lead. Confirmation of these claims by completely unbiased investigators, associated with neither the development nor the marketing of such steels, has been eagerly awaited. We are glad, therefore, to publish this article—a straightforward, entirely disinterested appraisal of a typical leaded steel, based on carefully made tests of material subjected to various heat treatments. The authors also offer some interesting conclusions on the effect of heat treatment and grain size on machinability, and some new ideas on "machinability" itself. —The Editors.

THE MODERN MANUFACTURER finds himself confronted constantly with the problem of speeding up production schedules so as to turn out more parts at less cost. His machine tool operations must, therefore, be accelerated to finish each part in a shorter time without increasing the maintenance and depreciation costs on his equipment. Often this must be accomplished without the addition of new equipment, and various free-machining steels have been widely used to permit faster production by resorting to higher cutting speeds and feeds.

Along with the need for lower fabricating costs has come the development of products many of which are subjected to severe service conditions that create a demand for increased strength of materials. This increase in strength is usually obtained at a sacrifice in the machinability of the steel used. Thus there is a definite need for a free-machining open-hearth steel that is of higher carbon content than the commonly-used screw stocks and which can be heat treated to obtain higher strength or hardness if desired.

Steel producers have investigated the chemical composition and manufacturing processes that will give the most easily machined metal having the necessary strength and heat treating properties. Recent articles[1, 2] have indicated that the addition of small amounts of lead to several open-hearth steels resulted in improved machinability without materially affecting the other physical properties of the steel. Leaded steels have been widely advertised as being readily machinable and can be obtained with various carbon contents suitable for heat treatment. For this reason it seemed desirable for a completely disinterested source to investigate the physical properties and relative machinability of one of these lead-bearing open-hearth carbon steels which have been placed on the market within the last 18 months.

The purpose of this investigation was to determine the ordinary static, impact, and fatigue properties of the steel and to measure by some laboratory process the relative machining qualities of leaded steel as compared with those of several other commonly used metals. The lead-bearing steel that was selected for test was an ordinary S.A.E. 1045 steel to which had been added (according to the manufacturers) about 0.20 per cent of lead. This is sold under the trade name "Ledloy." The chemical analyses of the lead-bearing steel and of the other metals used for comparison in the machinability tests are listed in Table I. All specimens of the lead-bearing steel were received in the form of ¾ in. dia. cold drawn bars, all from the same heat, and the steel was tested in three different conditions, namely: (a) cold drawn (b) normalized and (c)

Table I. Chemical Analyses of Steels and Irons Tested

Metal	Chemical Analysis, per cent							
	C	Mn	P	S	Si	Cr	Ni	Pb (Approx.)
Leaded Steel, (S.A.E. 1045 + Lead)	0.44	0.75	0.023	0.027	...	...	...	0.20
S.A.E. 3140*	0.37	0.71	0.015	0.020	0.21	0.61	1.40	...
S.A.E. 2345*	0.45	0.75	0.008	0.012	0.23	...	3.61	...
Plain-Carbon Steel*	0.49	0.46	0.017	0.029	0.12	...	...	...
High Test Cast Iron* Pearlite + Graphite	3.11	0.51	0.225	0.10	1.75	...	...	...
Gray Cast Iron*	3.56	0.59	0.450	....	2.25	...	...	...
S.A.E. X 1112*	0.08 to 0.16	0.60 to 0.90	0.09 to 0.13	0.20 to 0.30				

* Used only for machining tests.

y of a Leaded Steel

quenched-and-tempered. Standard laboratory tests were made to determine the physical strengths, and a special dynamometer drill press (see Fig. 5) was used to measure the relative machining qualities, which were evaluated by determining the horsepower required to drill small holes in each metal.

In an attempt to determine whether the grain size of a steel might be directly related to its machinability, some further heat treatments were given to the leaded steel and also to the S.A.E. 2345 steel to produce large grain size. The various heat treatments and resulting grain sizes of the steels tested are listed in Table II. Photomicrographs of the leaded steel in each of the conditions tested are shown in Figs. 1 and 2. Fig. 1 shows the structure of the metal as used in the physical strength tests, and Fig. 2 shows the large-grained steel which was used only in the machinability tests.

Mechanical Properties

The static tensile stress-strain curves for the lead-bearing steel in each of the three test conditions are shown in Fig. 3. These diagrams are more or less characteristic of ordinary plain carbon (non-leaded) steel. As might be expected, the cold-drawn material had no yield point, whereas both the normalized and the quenched-and-tempered leaded steel showed well marked yield points.

A summary of the results of the static physical tests of the lead-bearing steel is shown in Table III. An examination of the static tensile properties shows this steel to be of a type desired for many heat treating operations. The quenched-and-tempered steel evidences a marked improvement in ultimate tensile strength and yield point over those obtained from the normalized steel, and it also exhibits a slightly greater ductility than the cold-drawn steel. The improvement in hardness and modulus of rupture in torsion by the heat treatment further indicates that this steel would be of good heat treating quality. In general, the static physical properties listed in Table III are very similar to those expected from an ordinary carbon (non-leaded) steel and indicates that the addition of a small amount of lead did not appreciably impair the static physical strength properties in any way.

The values of Charpy impact strengths listed in Table III seem rather low, but are about in the range of values ordinarily obtained for non-leaded carbon steel under similar testing conditions. The exact significance of the impact test is not well understood, but the one recognized theory is that notched-

Table II. Heat Treatment and Resulting Grain Size

Steel	Treatment	Grains per sq. in. at 100 diam.	Grain Size A.S.T.M.	Brinell Hardness No.
S.A.E. 1045 + Lead	None; as received, cold-drawn	24–48	5–7	211
S.A.E. 1045 + Lead	Cooled in air after ¼ hr. at 1520 deg. F.	128	8	168
S.A.E. 1045 + Lead	Quenched in oil from 1520 deg. F. Tempered at 650 deg. F., air-cooled	128	8	248
S.A.E. 1045 + Lead	Air-cooled after 2 hrs. at 2200 deg. F.	3	2–3	194
S.A.E. 1045 + Lead	Furnace-cooled after 2 hrs. at 2200 deg. F.	3	2–3	149
S.A.E. 2345	Air-cooled after 2 hrs. at 2200 deg. F.	+1	—1	207
S.A.E. 2345	Furnace-cooled after 2 hrs. at 2200 deg. F.	+1	—1	207
S.A.E. 2345	Furnace-cooled after 2 hrs. at 2200 deg. F., reheated to 1450 deg. F. for 1 hr., furnace-cooled	64	7	212

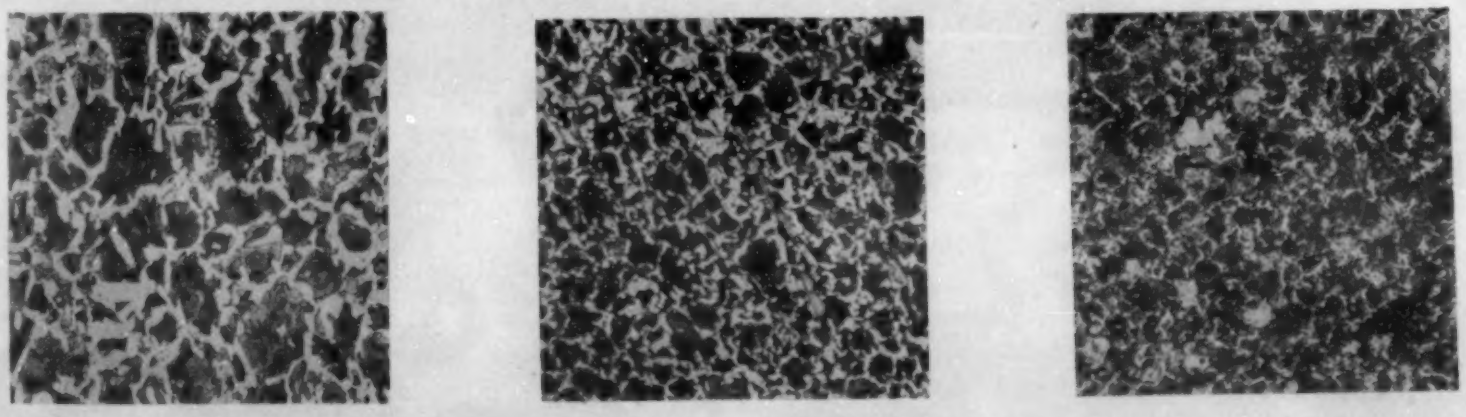


Fig. 1. Microstructure of S.A.E. 1045 + lead. Etched with 2% Nital; magnification, 130 X. At left, cold-drawn specimen, transverse section; center, normalized; right, quenched-and-tempered.

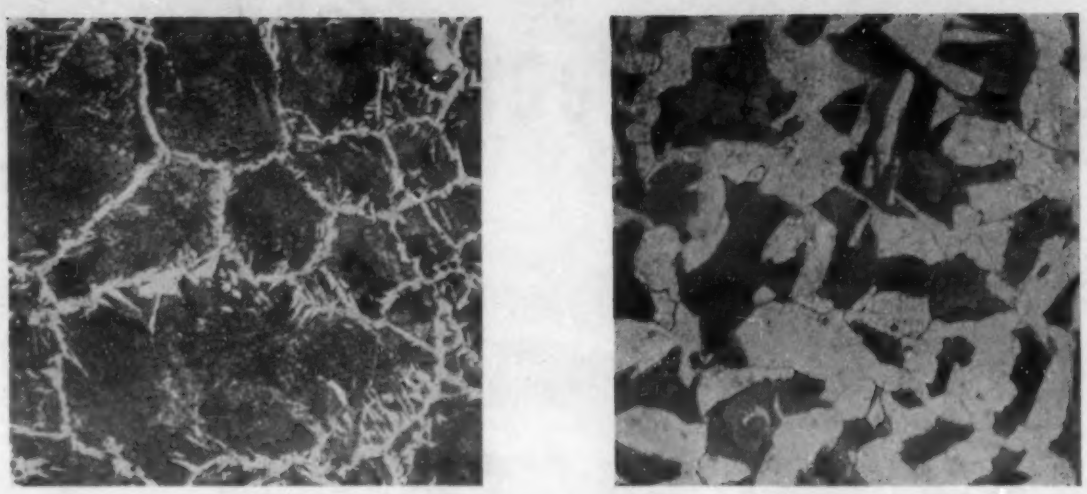


Fig. 2. Microstructure of large-grained S.A.E. 1045 + lead. Etched with 2% Nital; magnification, 130 X. At left, air-cooled after 2 hrs. at 2200° F.; at right, furnace-cooled after 2 hrs. at 2200° F.

bar tests give an indication of the cohesive strength of a material. However, the impact value for a material obtained from notched specimens probably is the sum of two energies, one of which is that absorbed by the specimen in preventing the *formation* of a crack, and the other is that absorbed by the specimen in resisting the *spread* of the crack. Unfortunately, the value obtained in making the test does not distinguish between these resistances but gives the sum of the two. A large portion of the increase in impact strength of the lead-bearing steel in the normalized condition over that in the cold-rolled condition may be accounted for by the increased resistance to the spread of a crack in the more ductile normalized steel. Similarly the steel is less ductile when quenched-and-tempered than when normalized, but its increased strength may offer a greater resistance to the formation of a crack; hence their two impact values do not differ appreciably.

Fatigue Properties

To investigate the relative fatigue strength and notch sensitivity of this steel, standard 0.300-in. dia. specimens were tested in Farmer-type rotating beam testing machines that subjected the specimen to completely reversed cycles of flexural stress, and the endurance limits of the leaded steel were determined for each of the three conditions. Tests were also made with 0.400-in. dia. cylindrical specimens with a small transverse-drilled hole (0.040 in. dia.) to determine the relative reduction in fatigue strength caused by the abrupt change in section of the specimen (notch effect). The standard specimens without the abrupt change in section will be referred to as "unnotched," while those containing the small transverse hole will be designated as the "notched" specimens. The nominal stresses in the fatigue specimens were calculated by the ordinary flexure formula on the basis of a solid circular cross-section; no allowance was made for the material removed by the hole in the notched specimens. The S-N curves showing the individual results for each specimen tested are plotted in Fig. 4.

The flexural fatigue endurance limit of the unnotched specimens of the quenched-and-tempered 0.45 per cent C steel with lead (63,000 lb. per sq. in.) is in close agreement with the value of 64,000 lb. per sq. in. reported by Robbins.[2] There was no apparent difference in the character of the fractures of the fatigue specimens of leaded steel from those of other wrought ferrous metals when tested under similar conditions. Comparison of the endurance limits of the steel in each of the three conditions, (see Table IV) permits several rather significant observations to be made. The marked improvement in the endurance limit of unnotched specimens of the quenched-and-tempered lead-bearing steel over that of the cold drawn or the normalized material was not in proportion to the increase in tensile strengths. For the normalized steel the endurance limit was 43 per cent of the ultimate tensile strength. By quenching-and-tempering, the endurance limit was raised 52 per cent while the ultimate tensile strength was raised only 32 per cent by the same heat treatment. It will be noted that the endurance limit of unnotched specimens of the quenched-and-tempered material (63,000 lb. per sq. in.) was higher than that of the cold drawn (48,000 lb.

Table III. Mechanical Properties of S.A.E. 1045 With Lead. Each value represents the average of 3 tests.

Property	Cold Drawn	Quenched and Tempered	Normalized
Ultimate Strength, lbs. per sq. in.	115,000	127,000	96,000
Yield Point, lbs. per sq. in.....	74,000 [1]	90,100	61,500
Reduction of Area,[2] per cent....	30.2	35.6	47.7
Elongation (8-in. gage length), per cent	5.25	8.62	20.7
Elongation (2-in. gage length), per cent	12.5	18.0	31.7
Modulus of Rupture [2] in Torsion, lbs. per sq. in.....	95,000	113,000	64,000
Brinell Hardness (3,000 kg.)....	211	248	168
Charpy Impact Strength,[3] ft.-lbs.	6.40	18.9	20.8

[1] Yield Strength, based on 0.2 per cent off-set.
[2] Solid Specimen ½ in. diameter.
[3] Using A.S.T.M. Std. 45-deg., V-notch specimen with 0.01 in. radius at root of notch.

per sq. in.) or normalized (41,500 lb. per sq. in.) steel, but when specimens having a hole were used, the endurance limit of the normalized steel (26,000 lb. per sq. in.) was higher than the cold drawn (19,000 lb. per sq. in.) or the quenched-and-tempered (20,000 lb. per sq. in.) steel. It can be seen that the quenched-and-tempered steel exhibited practically the same endurance limit as the cold-drawn steel when specimens with a hole were used, although there was a large difference between the endurance limits of the unnotched specimens.

The last column of Table IV lists the stress concentration factor, K, (ratio of the endurance limit of the unnotched specimen to that of the notched specimen) which gives a measure of the relative notch sensitivity of the steel. Also listed in Table IV are the results of some previous[3, 4] fatigue tests on two other steels which are listed here to show their relative notch sensitivity. The low carbon steel (S.A.E. 1020) is representative of a large group of low carbon steels that show comparatively small reductions in fatigue strength due to "stress raisers," whereas the alloy steel (S.A.E. 3140) is one of the more "notch-sensitive" materials whose fatigue strength is greatly reduced by an abrupt change in section. It will be noted that the value of the stress concentration factor, 3.15, for the quenched-and-tempered leaded steel was much higher than the values of K for these two steels. In some previous tests of four low-alloy steels[4] the average value of the stress concentration factor was found to be 2.23 when employing specimens of the same size and shape as those used to obtain the data in Table IV. Thus it will be observed that the normalized lead-bearing steel showed a lower stress concentration factor than many of the commonly-used steels, but the cold-drawn and the quenched-and-tempered lead-bearing steel exhibited a greater notch sensitivity than most of the other steels tested. If cold-drawn or quenched-and-tempered leaded steel were to be used in a machine part expected to withstand a large number of cycles of stress during its normal operation, then its notch sensitivity would be of great importance and should be taken into consideration in the design of the part.

It is a recognized fact that fine-grained quenched-and-tempered alloy steels, having relatively high endurance limits as determined by using unnotched specimens, normally exhibit greater notch sensitivity than the lower carbon steels which have not been subjected to hardening operations. For some steels test results show a large difference between the endurance limits of notched and unnotched specimens whereas in other steels only a small difference is obtained; this is a phenomenon that engineers have never been able to explain fully. Perhaps the notch-sensitivity may be in some way related to the relative amount of deformation at the yield point

Table IV. Fatigue Properties of S.A.E. 1045 with Lead. Specimens subjected to completely reversed cycles of flexural stress.

Material	Endurance Limit, lbs. per sq. in. Un-notched	Endurance Limit, lbs. per sq. in. Notched [1]	Stress Concentration Factor, K [2]
S.A.E. 1045 + lead, cold-drawn	48,000	19,000	2.53
S.A.E. 1045 + lead, normalized	41,500	26,900	1.60
S.A.E. 1045 + lead, quenched-and-tempered	63,000	20,000	3.15
S.A.E. 3140, hot-rolled	64,000	31,000	2.06
S.A.E. 3140, quenched-and-tempered	90,000	31,000	2.90
S.A.E. 1020, hot-rolled	29,500	16,000	1.84

[1] Specimen 0.40 in. dia., with a transverse drilled hole 0.04 in. dia.

[2] $K = \frac{\text{Endurance limit unnotched specimen}}{\text{Endurance limit notched specimen}}$

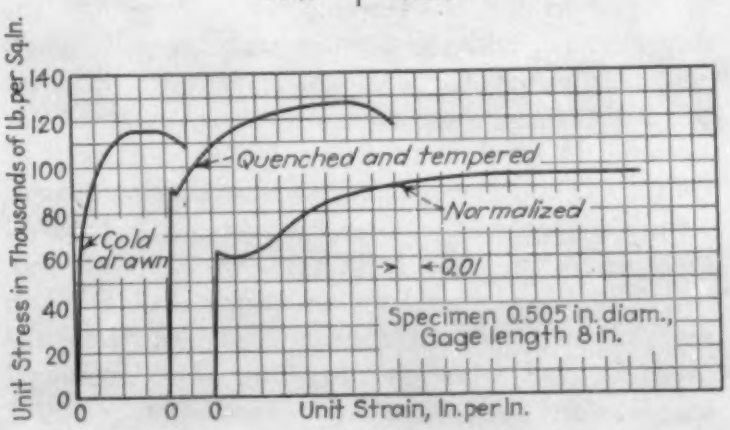
of the material since the localized plastic action occurring around abrupt changes in section has a great influence on the beginning of fracture. For instance, the quenched-and-tempered material showed less elongation at the yield point than did the normalized material and also showed a greater stress concentration factor. This fact, which has also been observed in several other tests, might be a characteristic behavior of many ductile steels and should merit a more complete study.

Machinability Tests

Before discussing the machinability tests, perhaps the first idea to consider is raised by the question: "What *is* machinability?". The term "machinability" is entirely relative and may mean any or all of a variety of qualities or properties. For example, machinability may be measured by the relative tool life, by the power or energy required to perform an operation, by the type of chip formed in cutting, by the smoothness and dimensional accuracy obtained in the finished product, or by the time required to complete a given cutting operation (for example, the time required to make a given saw cut).

The terms used to express machinability are not entirely comparable and express only the characteristic behavior of a metal under a given set of conditions.

Fig. 3. Static tensile stress-strain diagrams for S.A.E. 1045 + lead.



For a given metal some of the variables to be considered in machinability comparisons might be: the tool material and shape of the tool, the size and shape of the cut, the cutting fluid, and the relative surface speed of the cutting operation. All of these variables must be kept constant in order to form any conclusion about the relative ease with which metals may be machined.

In view of these considerations, perhaps no single test will ever be devised that will include the many variables involved and give a complete index of the machinability of a steel. For this reason, laboratory tests to determine machinability are not strictly dependable and give only an indication of the trends to be observed in a particular type of cutting operation, in which a given set of variables are controlled. Thus the laboratory machinability test chosen by the authors does not include many of the factors affecting machinability, but it is felt that the test employed does yield information on one phase of the relative machinability of leaded steels.

The laboratory tests that were made to determine the relative machinability of the leaded steel as compared with several other metals were conducted by drilling ¼-in. holes in each metal and observing simultaneous values of torque and thrust on the drill by means of dynamometer readings. Fig. 5 shows the dynamometer drill press used in these tests. The vertical spring, A, resists the thrust on the specimen being drilled, and the deformation of the spring can be observed by readings of the dial, B. Similarly the spring, C, resists the torque on the specimen, and its deformation is obtained from dial, D; these dial readings can then be calibrated to yield values of the thrust in lbs. and the torque in in.-lbs. that are transmitted to the specimen by the drill.

The testing procedure consisted of drilling one hole in each metal in succession and observing simultaneous dial readings of torque and thrust on the drill. The operation was then repeated 6 times, drilling the metals in the same sequence each time. It was felt that this procedure would allow for any variation in dynamometer readings caused by tool wear, and would distribute the observed differences evenly throughout the 6 values obtained for each metal. In general, there were only small variations observed in the 6 dynamometer readings for any one material, and the average readings gave representative values for comparison between different materials. From these average readings obtained, the horsepower required to drill a ¼-in. hole could be computed, and the relative machinability was based on this horsepower requirement. A ¼-in. Cleveland twist drill that had a helix angle of 22° was used, the drill being ground on an Oliver drill grinding machine. A standard cutting fluid was circulated over the drill while in operation. Two rotational speeds were used in these tests (1460 and 915 r.p.m.), which gave corresponding surface speeds of 90 and 60 ft. per min. Only one feed was used, namely 0.0085 in. per revolution, which, of course, gave faster feed with the higher speed.

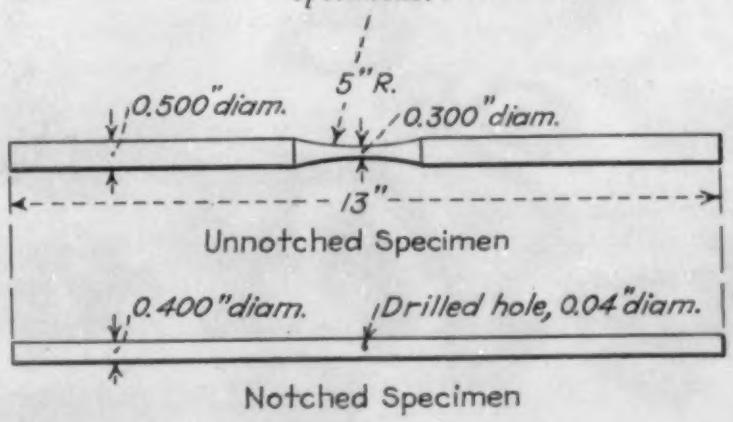
It was also felt desirable to investigate the effect of variation of pearlitic grain size upon the machinability of the leaded steel and the S.A.E. 2345 steel. The pearlitic grain size was changed by heating the specimens to 2200° F., holding for 2 hrs., and then cooling in air or in the furnace. Table II gives the heat treatments and resulting sizes of pearlitic grains as determined at a magnification of 100 X.

Comparison of Machinabilities

An examination of the test data in Table V brings out several significant facts. The power requirements at the slower speed (60 surface ft. per min.) for the specimens of leaded steel were lower than for any other material tested except for the cast irons and the screw-stock steel, S.A.E. X 1112. The non-leaded carbon steel of very nearly the same composition, but of lower strength and hardness, required considerably more power. The 2 alloy steels likewise required greater power than the lead-bearing steel although the S.A.E. 3140 had very nearly the same ultimate strength and hardness, and the S.A.E. 2345 had lower ultimate strength and hardness than the quenched-and-tempered lead-bearing steel. For the slower speed, the normalized and the large-grained leaded steel required more power than did either the cold-drawn or the quenched-and-tempered material. The cold-drawn leaded steel showed very nearly the same power requirement as the screw stock material S.A.E. X 1112. This is rather significant in that the leaded steel tested had a very much higher percentage of carbon than the screw stock and was not of a carbon content that is ordinarily thought of as that of a free-cutting steel.

When the higher speed (90 surface ft. per min.) is considered, it is observed that again the specimens of leaded steel machined more readily than the other metals with the exception of the cast irons and the free-cutting screw stock steel. At this speed,

Fig. 4a. Shape and dimensions of flexural fatigue specimens.



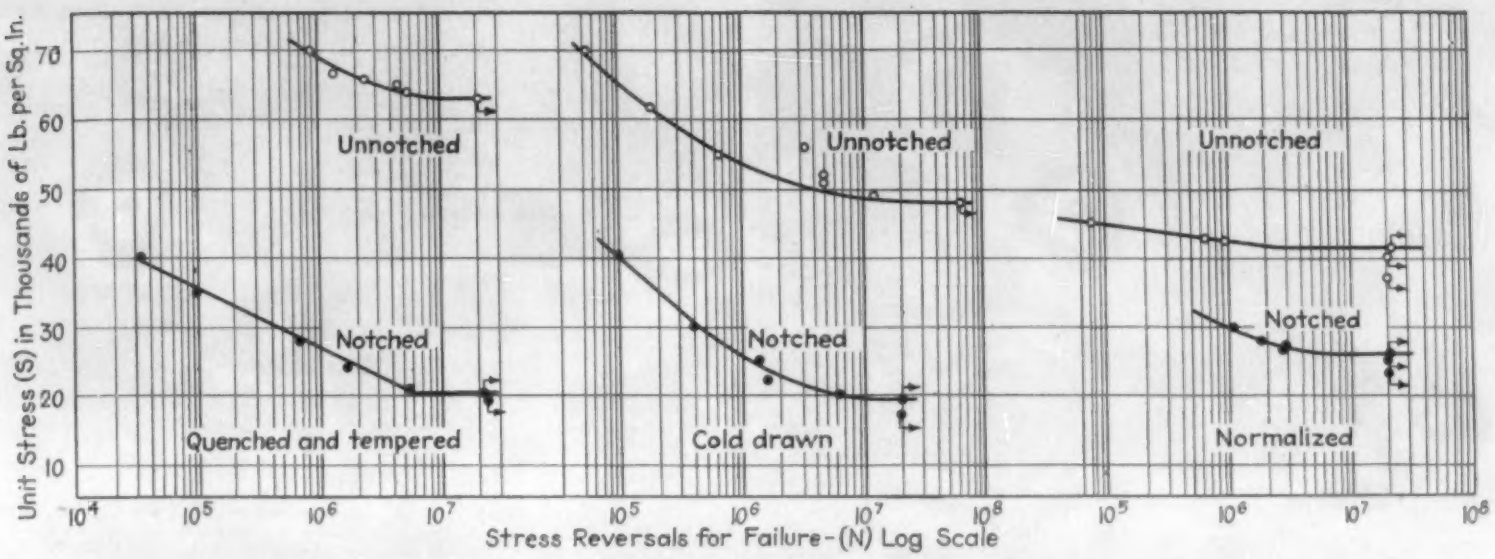


Fig. 4. Fatigue properties (S-N diagrams) of S.A.E. 1045 + lead, notched and unnotched, and after various treatments. See Fig. 4a for specimen dimensions.

however, the normalized and the large-grained leaded steel machined easier than the quenched-and-tempered or the cold-drawn steel. In fact the power required by the large-grained and by the normalized steel containing lead was less in each specimen than that required for the screw stock material. The gray cast iron required very nearly the same power regardless of the speed of drilling although all of the other metals showed an increased power requirement at the higher speed. The two specimens of large-grained S.A.E. 2345 and the two specimens of large grained leaded steel exhibited a rather peculiar behavior. At 60 surface ft. per min. the furnace-cooled specimens required the lesser power, while at the 90 surface ft. per min. the air-cooled specimens machined the easier.

A comparison of the machining power requirements with some of the physical strength properties as listed in Table V would indicate that there is apparently no direct correlation between the machinability of the steel as measured by the horsepower requirements and the static physical properties of the material. For instance, the Brinell hardness of the material is not a direct index of the relative machinability nor is the ultimate tensile strength directly related to the power required to drill a small hole in the metal. The grain size of a steel is often thought to be an indication of its relative machinability; some authors contend that large grains split more easily than small grains, but this is probably not strictly correct. The apparent brittleness of coarse-grained material is probably due to the fact that there are fewer changes in direction in the path of a spreading crack through a specimen of large-grained material than there would be through a similar specimen of fine-grained material. The data in Table V tend to show that the grain size of a steel is not necessarily an indication of the ease with which it may be machined. In one case the large-grained specimens of leaded steel required practically the same power as the normalized finer-grained material, whereas for the S.A.E. 2345 steel the machine-power requirements were slightly greater for the coarser-grained steel at the lower drilling speeds, but at the higher drilling speeds the finer-grained material would not drill. The tool wore out very rapidly and became dulled beyond use in a few moments. The observation that the leaded steel could be readily

Table V. Results of Machinability Tests. Relationship between power requirements for drilling 1/4-in. hole, and the hardness, grain size, and ultimate strength of steel.

Material	Brinell Hardness	ASTM Grain Size	Ultimate Strength, lbs. per sq. in.	Horse Power Required: at 90 surface ft. per min.	Horse Power Required: at 60 surface ft. per min.
Leaded steel, cold-drawn	211	5–6	115,000	0.551	0.372
Leaded steel, quenched-and-tempered	248	8	127,000	0.615	0.390
Leaded steel, normalized	168	8	96,000	0.527	0.428
Leaded steel, air-cooled after 2 hrs. at 2200 deg. F.	194	2–3	.....	0.502	0.431
Leaded steel, furnace-cooled after 2 hrs. at 2200 deg. F.	149	2–3	.....	0.525	0.420
0.49% C steel, normalized, quenched-and-tempered	180	1–3	94,300	0.700	0.456
0.49% C steel, normalized	164	6–8	91,500	0.835	0.527
S.A.E. 3140, hot-rolled	235	6–8	127,000	0.789	0.452
S.A.E. 2345, air-cooled after 2 hrs. at 2200 deg. F.	207	—1	114,000	0.623	0.537
S.A.E. 2345, furnace-cooled after 2 hrs. at 2200 deg. F.	207	—1	114,000	0.640	0.514
S.A.E. 2345, furnace-cooled from 1450 deg. F. after normalizing	212	7	110,000	....*	0.506
High-test cast iron	231	...	54,800	0.437	0.398
Gray cast iron	139	...	20,500	0.297	0.287
S.A.E. X 1112	141	8	72,500	0.537	0.360

* Would not drill.

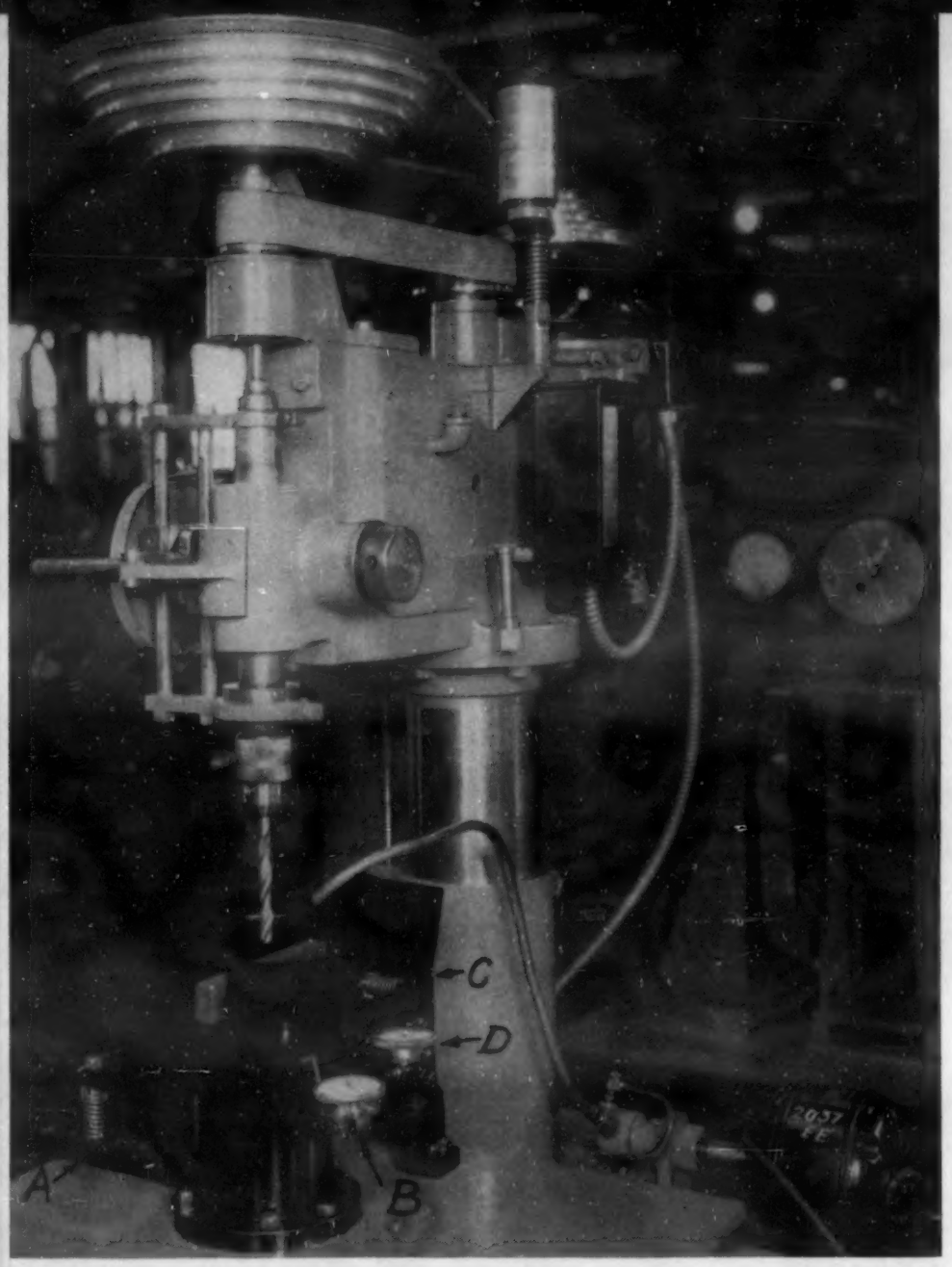


Fig. 5. Dynamometer drill press used in machinability tests.

drilled at 90 surface ft. per min., whereas the fine-grained S.A.E. 2345 of lower strength could not be drilled at this higher drilling speed, suggests that lead-containing steels might be commercially machinable at higher strength and hardness levels than some of the lead-free steels.

It has been observed in some instances[5] that the Charpy impact values may give some indication of the relative machinability of the metal. If the cutting of a metal may be regarded as a localized fracture it seems reasonable that the type of action taking place in machining may be that of a relatively rapidly applied load involving impact and also including the factor of notch sensitivity. The energy absorbed in a cutting operation may be closely related to that required to form a crack and that required to propagate the crack in the material. It is not unreasonable to find, therefore, that the Charpy impact value may give a rough index of the machinability of a steel; perhaps in the future some type of impact test may be devised that will give a usable criterion for machinability of a metal. However, in the present tests no definite correlation was obtained between the Charpy impact values and the machinability power requirements as obtained from the drill dynamometer tests of the leaded steel.

General Discussion

When a new material (such as a leaded steel) is introduced on the market, the consumer must generally give it careful consideration if he wishes to use it to replace a material that has proved satisfactory in service. The two main questions he must decide for each individual application are: (1) "Is it technically useful?" and (2) "Is it more economical?" The question of technical worth includes those qualities of interest to the engineer or technical man and includes not only the relative physical strengths under service conditions, the metallurgical aspects of its manufacture and heat treatment and the machinability, but other factors such as the possibility of flame cutting, welding, and forging, without impairing the physical properties. The economic aspects of the new material are based on the total cost per unit of the finished product. Thus it includes the initial cost of the material and all processing costs such as relative tool wear, production speeds on individual parts, and initial costs of setting up equipment to obtain optimum operating conditions. To obtain maximum economy, the optimum speeds for each particular machining operation must be carefully determined if the use of a higher-priced steel is to be justified. Unless it is essential to produce increased output without adding new machine tool equipment, the higher initial cost of a material may largely offset the increased production speed unless full advantage is taken of the greater ease of machinability. However, no saving can be expected if the machine tool equipment is already operating at high speed and cannot be speeded up to make use of the higher optimum speeds which appear to be permissible with the leaded steels.

Judging from the mechanical properties as obtained from laboratory tests, the technical worth of the leaded steel described above probably would be about the same as that of the same steel without the lead addition except for the item of machinability. Economically the leaded steel is more expensive in initial cost, but the laboratory machinability tests indicate that in many applications a saving can probably be made in processing costs and in the general speeding up of production. This may result in a lower total cost per unit of the finished product unless considerable additional equipment is required to overcome health hazards due to lead fumes in welding and flame cutting operations.

Acknowledgment

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the work of the Engineering Experiment Station of the University of Illinois of which Dean M. L. Enger is the Director, and of the Department of Theoretical and Applied Mechanics of which Professor F. B. Seely is the Head. The authors are indebted to Mr. C. J. Starr of the Department of Mechanical Engineering for his cooperation in making available the drill dynamometer and for his help in carrying out the machinability tests.

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The Fatigue Endurance of Killed, Capped and Rimmed Steels

by J. F. McDOWELL

Firestone Steel Products, Akron, Ohio.

Last year, in the May to December issues inclusive, we published a series of six important and valuable articles on the general subject of Fatigue of Metals. We feel that this article by Mr. McDowall supplements the series and comes as a suitable closure—it deals with the steels as they are made.

It is shown by the author that killed, capped and rimmed steels of about the same composition and nearly identical physical properties vary quite definitely in their ability to withstand repeated stress reversals; and that in calculating limiting stresses, cognizance of this fact should be taken where either capped or rimmed steel is involved.—The Editors.

THE FAILURE OF STEELS under repeated stresses below their ultimate tensile strength and even below their elastic limit presents a serious problem to the metallurgist and engineer alike. This phenomenon of steel failures with loads below the tensile strength has been known and studied for many years. In 1864, Sir W. Fairbairn published some results on a riveted wrought iron girder subjected to repeated stresses. He included in his report some earlier experiments made by Captains James and Gaston. Fairbairn concluded, from his experiments, that it was not safe to use a repeated stress which was more than one-third of the ultimate strength.

In 1870, Wohler published the results of a very exhaustive set of tests, the important conclusions of which were: (1) Wrought iron or steel will rupture at a unit stress much below the ultimate strength and even below the elastic limit, if repeated a sufficient number of times. (2) Within certain limits, the range of unit stress, not the ultimate stress, determines the number of repetitions for rupture. (3) As the range is diminished for a given maximum or minimum unit stress, the repetitions for rupture increase. (4) For a given maximum or minimum unit stress, there appears to be a limiting range for

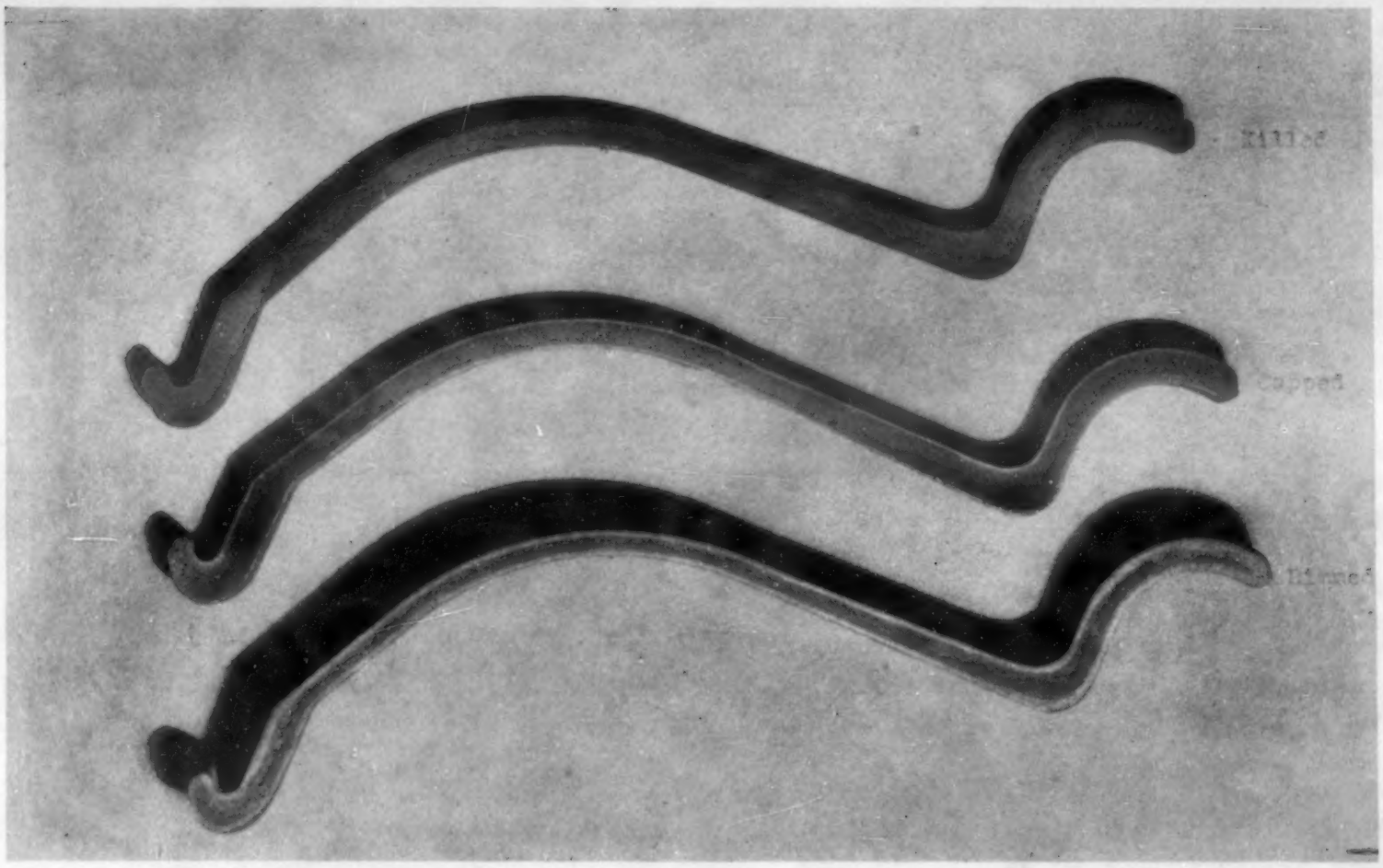


Fig. 1. Etched sections of killed, capped and rimmed steels.

which repetitions for rupture become infinite. (5) As the maximum unit stress increases, the limiting range of stress diminishes.

In many forms of steel constructions, the subject of fatigue, *i.e.,* endurance, is a vital one. This is particularly true in the manufacture of rims for truck, bus, and automobile wheels. The application of our knowledge of fatigue and the study of endurance problems has added many thousands of rim and wheel miles to the normal service of these products.

In calculating working stresses, it has been the rule, generally, to figure the endurance limit of steels at between 45 and 50 per cent of their tensile strength. For many steel parts, steels produced by different processes are used. In the manufacture of rims, for example, killed, capped, and rimmed steels all find an outlet. While these steels may vary only slightly in general physical properties, and chemical analyses, they are structurally different at the skin and hence, vary quite materially in endurance.

With this in mind, work was conducted to find the endurance values of the above group of steels, all of approximately the same chemical analysis and physical properties. The work consisted of chemical, physical, micro and macro analyses of specimens, representing the three classes of steels, together with their endurance values as determined from flat specimens on a machine designed for this type of work. Before recording the data found in these tests, a brief description of the different steels and a few details of the fatigue testing machine are given.

Type of Steels Used in Test

Killed steels are fully deoxidized steels and when poured into ingot molds, show no turbulence, but lie quiet, or "dead." A properly made killed steel is a high grade product and is specified for certain classes of high quality work.

The chemical analysis of the killed steels used in the production of rims and wheels varies only slightly from that of the capped or rimmed variety; it is usually distinguishable from the others, however, by its silicon content which is normally between 0.15 and 0.30 per cent. Higher silicon contents, of course, are often found and conversely, when other deoxidizers are used to completely kill the steel, the silicon content is sometimes below 0.10 per cent.

Capped steels, or semi-killed steels, are only partly deoxidized and, through their action in the ingot mold, develop an extremely thin, low carbon outer skin or case. The further development of the refined skin on the outside of the ingot is checked by quickly chilling or capping the top of the ingot.

Rimmed steels are so called because of their well developed low carbon skin or rim. They find many applications for deep drawing purposes where a

ductile outer skin is advantageous. The rimming of the ingot is produced because of a lack of suitable deoxidizing agents which permits a violent mold action. With the evolution of gases inward and upward from the ingot, non-metallic inclusions, together with some of the carbon (and possibly other elements) become segregated toward the center. This refining of the skin, which eliminates the columnar crystals of the ingot at this point, results in the formation of the ductile rim.

Fig. 1 shows sections of killed, capped, and rimmed steels which have been ground and deep etched to bring out the macro structures. The case and core of the capped and rimmed steels are clearly evident. Photomicrographs, Figs. 2, 3, and 4 show the microstructures of these same steels. The amount of pearlite at the edges of the specimens is what can be considered normal for each class indicated. Table 1 shows the chemical analysis of the steels used for test.

In Table 2 are shown the physical properties of the same steels. The test bars for physical tests and the millings for chemical analyses were taken from the same mill section. It should be noted that the variations in the properties listed, both physical and chemical, are very slight.

Type of Machine Used in Fatigue Tests

The machine used was the Krouse flat sheet fatigue machine which is designed to test sheet and plate under repeated bending stresses. (Fig. 5). It is of the fixed deflection type and uses the specimen as its dynamometer.

In effect, it represents a horizontal beam where the application of cross bending stresses elongates the fibres of the convex surfaces and shortens those of the concave surfaces. With the machine in operation, alternate tensile and compressive forces are imposed upon the fibres between the neutral and outer surfaces of the specimen.

Any desired stress within the limits of the machine can be applied to the specimen at its critical section. The load necessary to produce any given stress is obtained by use of the flexure formula

TABLE 1.—Chemical Analyses of the Steels Used

C	Mn	P	S	Si	Ni	Cr
			Killed			
0.20	0.50	0.012	0.034	0.16	Nil	Nil
			Capped			
0.21	0.45	0.016	0.037	0.038	Nil	Nil
			Rimmed			
0.25	0.38	0.010	0.035	Nil	Nil	Nil

TABLE 2.—Physical Properties of the Same Steels in Table 1

Tensile strength, lbs. per sq. in.	*Yield point, lbs. per sq. in.*	*Elongation on 2 in.*	*Reduction of area*	*Brinell hardness*	*Rockwell hardness*
		Killed			
63,650	38,550	41.4	56.6	131	B 75
		Capped			
64,960	38,630	40.7	56.6	134	B 74
		Rimmed			
64,550	38,710	43.2	56.0	128	B 68

The results given above are the average of two test bars.

Fig. 2. Killed steel showing pearlite undiminished to the edge. Etched with nital and picric acid. 100 X.

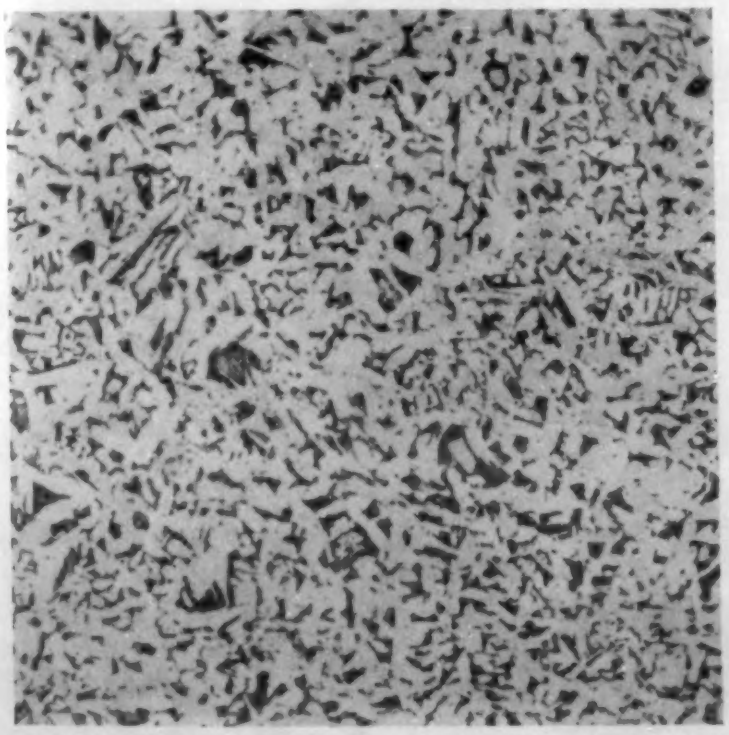
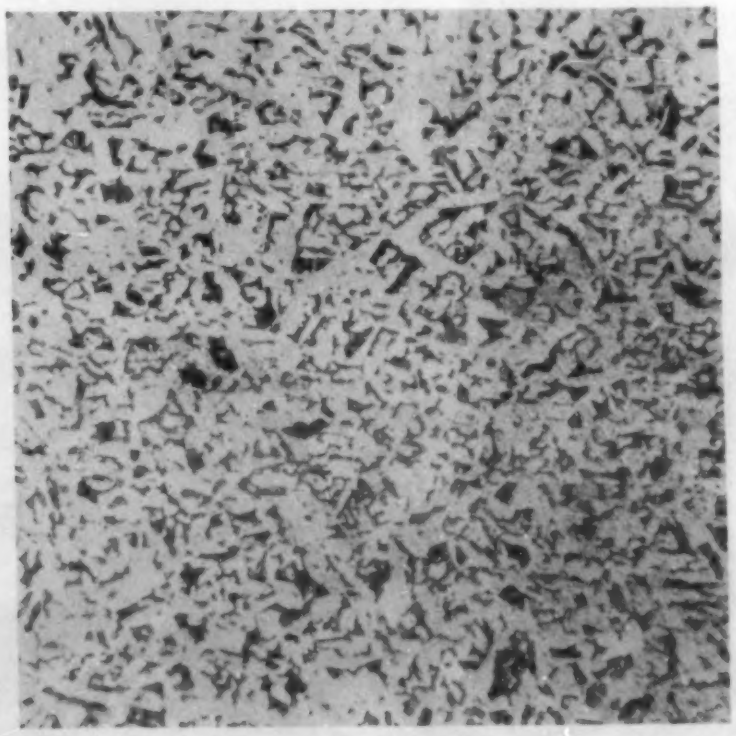


Fig. 3. Capped steel with slightly less pearlite appearing at the edge. 100 X.



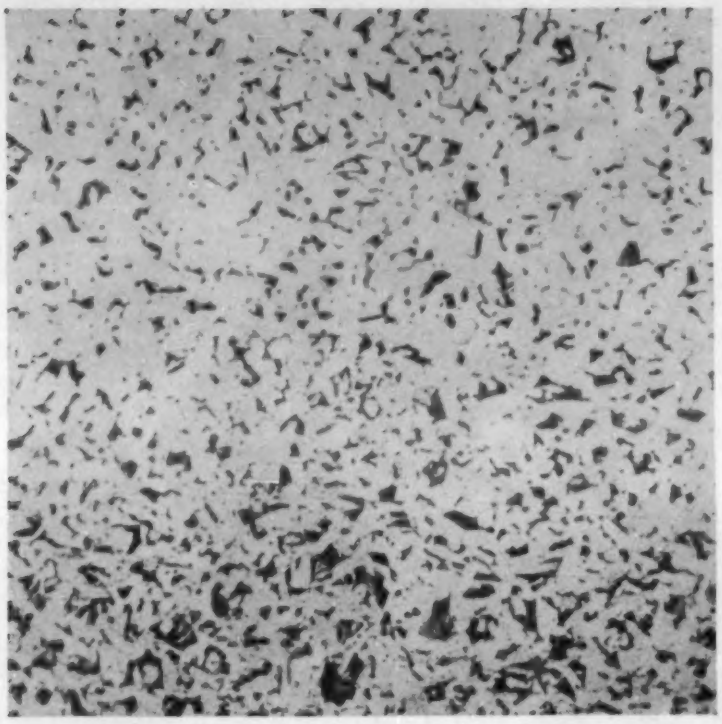


Fig. 4. Rimmed steel with its typical low carbon edge. 100 X.

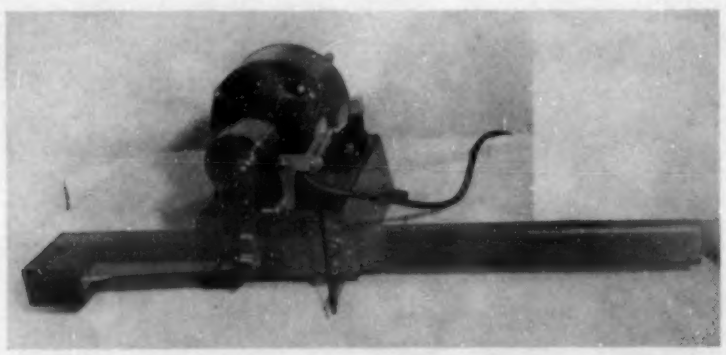


Fig. 5. The Krouse flat sheet fatigue machine.

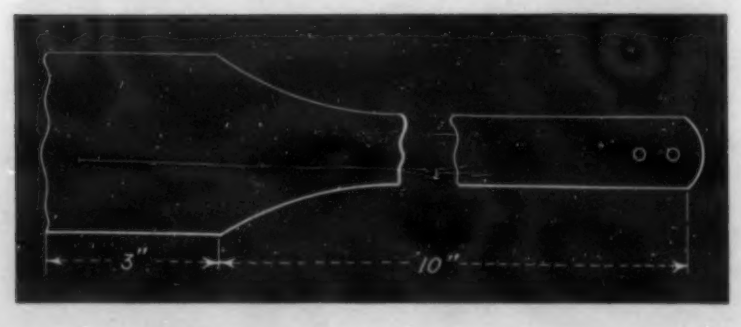


Fig. 6. Dimensions of the fatigue test pieces.

$$P = \frac{Sbd^2}{6L}$$

where

P = The load in lbs.
S = The stress in lbs. per sq. in.
L = Lever arm
B = Breadth
and D = The thickness of the specimen

A static load-deflection curve can be obtained by applying various loads at the axis of the connecting pin which fits snugly into the bushing of the specimen connector. The deflection is measured by a pointer attached to the end of the specimen connector. Movement of the pointer is measured on a scale rigidly attached to a movable holder at the base of the machine.

The machine operates at 1,850 revolutions per minute. In operation, one complete cycle of the motor gives one complete cycle of stress, or in starting from zero load and rotating the crank 90 deg. to its highest position, the upper surfaces of the specimen will be under maximum compression. By completing the cycle in 90 deg. steps, the same surfaces will come from maximum compression to zero load, to maximum tensile, and then to the original no-load position.

The cycles of stress are registered on a counter located at the rear of the machine.

Results of Fatigue Test

A sketch, showing the dimensions of the fatigue test pieces removed from regular rim sections (before cold working) is shown in Fig. 6.

The data obtained from the fatigue test specimens are given in Table 3. Plotting these fatigue data, using stress as ordinates and the number of cycles of stress as abscissae, a stress-cycle diagram for each steel was prepared. This is shown in Fig. 7.

TABLE 3.—Fatigue Endurance Data

Stress, lbs. per sq. in.	No. of Cycles	
Killed Steel—Not Decarburized		
31,250	16,306,000	Did not break
32,480	10,250,000	Did not break
33,010	7,182,000	
34,750	6,555,000	
37,700	1,113,000	
39,000	611,000	
Capped Steel		
25,200	10,108,000	Did not break
26,000	15,778,000	Did not break
27,150	12,714,000	Did not break
27,750	2,034,000	
29,130	3,854,000	
35,600	253,000	
Rimmed Steel		
23,400	10,058,000	Did not break
24,000	951,000	
24,100	10,440,000	
24,600	5,022,000	
26,660	406,000	

The endurance limits as shown in the preceding stress cycle diagram are as follows:

(a) Killed Steel——Not Decarburized
32,000 lbs. per sq. in.

(b) Capped Steel
27,000 lbs. per sq. in.
(c) Rimmed Steel
24,000 lbs. per sq. in.

The fatigue endurance ratio $\frac{\text{Fatigue Endurance}}{\text{Tensile Strength}}$, computed from the preceding data, is as follows:

(a) Killed Steel—Not Decarburized
0.50
(b) Capped Steel
0.42
(c) Rimmed Steel
0.37

It can be seen from the above that the use of the usual 50 per cent of the tensile strength of a member as being representative of safe working stresses holds true only in the case of the killed steels.

Cause of Variation in Fatigue Endurance of Various Steels

In order to show that the low fatigue values of the capped and rimmed steels are primarily due to a thin outer skin of low carbon composition, work of the following order was undertaken: A killed steel was selected, showing no decarburized edge. The chemical analysis of this steel was:

Carbon	0.21
Manganese	0.54
Phosphorus	0.011
Sulphur	0.033
Silicon	0.18
Nickel	Nil
Chromium	Nil

Fatigue and tensile specimens of the above were made and then decarburized in moist hydrogen ($Fe_3C+2H_2 \leftrightarrows 3\ Fe+CH_4$). This reaction was carried out at 1,600 deg. F., the time at temperature being approximately 3 hrs. A similar set of samples was given an exactly similar heat cycle, but in a neutral atmosphere as opposed to the moist hydrogen atmosphere which produced decarburization. The extent of decarburization produced through heating in moist hydrogen is shown in Fig. 8. Fig. 9 shows the same steel with the same heat treat cycle but without the decarburizing moist hydrogen atmosphere.

Static tests on the decarburized and heat treated (but not decarburized) samples were made and are shown in Table 7. Also shown, are the physicals of this same steel as received from the mill without any heat treatment.

(1) As Received, (2) Heat Treated in Neutral Atmosphere at 1,600° F., and (3) Heat Treated at 1,600° F. in Moist H_2. Fatigue test data on this series of steels are shown in Table No. 8. Curves plotted from the above data are shown in Fig. 10.

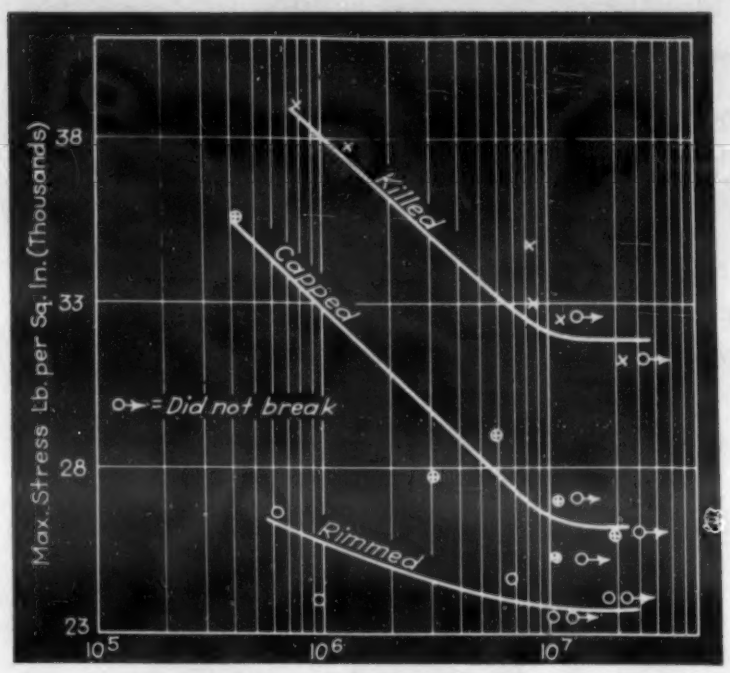


Fig. 7. Stress cycle diagram for killed, capped and rimmed steels.

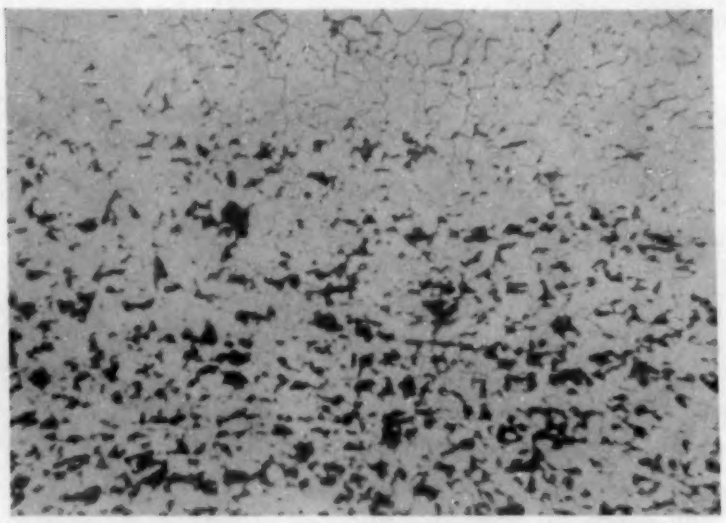


Fig. 8. Decarburized case on killed steel. 100 X.

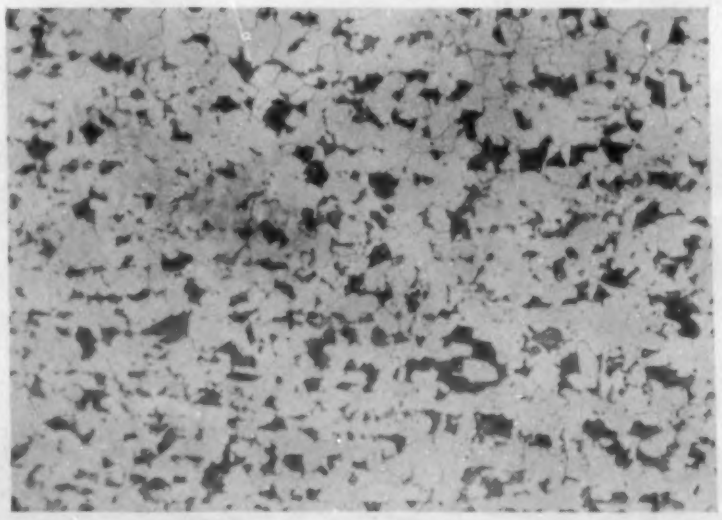


Fig. 9. Control sample, similar heat treatment, but not decarburized.

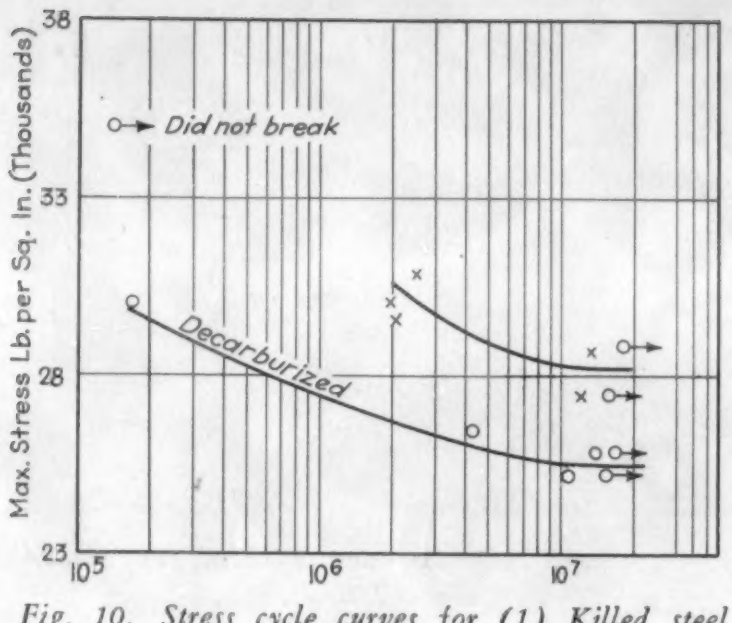


Fig. 10. Stress cycle curves for (1) Killed steel decarburized in moist H_2 at 1600 deg. F. (2) Killed steel given the same heat cycle, but in a neutral atmosphere.

TABLE 7.—Physical Properties of Killed Steel—

Tensile strength lbs. per sq. in.	Yield point, lbs. per sq. in.	Elongation on 2 in.	Reduction of area	Brinell hardness	Rockwell hardness
1. 65,680	41,750	39.0	60.6	131	B 76
Killed Steel as Received Not Decarburized					
2. 58,960	36,720	40.4	50.2	126	B 74
Decarburized					
3. 59,100	36,465	43.0	49.7	126	B 70

TABLE 8.—Endurance Limits

Killed Steel—Not Decarburized

Stress, lbs. per sq. in.	No. of Cycles	
27,500	10,717,000	Did not break
28,750	11,797,000	Did not break
29,560	2,646,000	
30,050	1,556,000	
31,100	1,762,000	
Killed Steel—Decarburized		
25,250	10,354,000	Did not break
25,850	13,815,000	Did not break
26,500	2,799,000	
27,500	815,000	
30,000	147,000	

These data indicate that when heat treated but not decarburized, this particular killed steel shows an endurance limit of around 28,250 lbs. per sq. in. This gives an endurance ratio of approximately 0.48 which is close to the 0.50 range generally used. The decarburized sample, on the other hand, shows an endurance limit of around 25,500 lbs. per sq. in. or 2,750 lbs. per sq. in. less than the control sample. With an ultimate tensile strength of 59,100 lbs. per sq. in., this gives an endurance ratio of 0.43 for the decarburized killed steel. This, it can be seen, is in the range of the capped steels which gave an endurance ratio of 0.42.

Conclusions

Killed, capped, and rimmed steels of approximately similar chemical and nearly identical physical properties have been shown to vary quite definitely in their ability to withstand repeated stress reversals. In the calculation of limiting stresses, cognizance of this fact should be given when either a capped or rimmed steel is involved.

Decarburized surfaces on medium or high carbon steels have been shown to drastically reduce the fatigue resistance of these steels A. L. Boegehold, *Metal Progress,* Vol. 31, Feb. and Mar., 1937, pp. 142-152, 265-269.) Skin decarburization has now been seen to influence the fatigue endurance of a low carbon steel *i.e.,* 0.21 per cent carbon. In the case of rimmed or capped steels, this skin effect is unquestionably responsible for their inability to withstand repeated stress reversals on a plane with the normal carbon-skin killed steel.

Segregation of other elements, particularly in rimmed steels, might possibly contribute to the lowering of the fatigue resistance of this type of steel. However, in view of the light of this work, the segregation of elements other than carbon away from the skin of the metal can be considered to play a very minor role in the effect upon fatigue properties. That the carbon content of a steel is important when viewed from the angle of fatigue, is shown by the well known fact that the fatigue resistance of steel increases with its carbon content up to approximately eutectic composition.

Viewed again from the fatigue angle, the role of carbon is doubly important at the skin of a steel when it is considered that the removal of this element through decarburization lowered the endurance ratio of a killed steel sufficiently to place it in the category of the lower fatigue resistant capped steels.

The author appreciates the permission of the Firestone Steel Products for publication of the data recorded.